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Keywords:	energy-, bandwidth-, power-efficiency, resource allocation, interference management, HetNets, simulation, algorithms

Authors

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Executive Summary

The objective of WP1.3 is the study of bandwidth and energy efficiency techniques, applicable to current and emerging wireless systems and networks. This work is highly relevant to current trends in wireless systems, where the combined proliferation of services/applications and hardware infrastructure has led to increased energy requirements for all the network elements.

Based on the Newcom# participants' interests and expertises, the WP is divided into three Tasks, each with specific scope and objectives. Task 1.3.1 "Techniques for power-efficient communications" deals with techniques for power efficiency and minimization at the transceiver and network level. Task 1.3.2 "Low-interference, low-emission, radio interfaces" deals with the handling of interference by appropriate low interference transmission techniques (e.g. beam-forming, MIMO, GMC). Task 1.3.3 "Resource Allocation for optimized radio access" is about Radio Resource Management (RRM) and Interference Management (IM) – for a given interference level – in selected scenarios of interest.

In each Task, the work is organized in specific Joint Research Activities (JRAs) in order to enhance cooperation between partners and promote research harmonization. JRA 1.3.3D was included in the second year of the project; a SWOT (Strengths Weaknesses Opportunities Threats) analysis was presented and assessed at the Newcom# WP1.3 meeting in Lisbon on January 2014. The active JRAs at the end of the second year of the project are the following:

- JRA 1.3.1A on resource allocation and scheduling strategies for energy harvesting devices

- JRA 1.3.1B on energy-efficient data collection and estimation in wireless sensor networks

- JRA 1.3.1C on Joint Protocol Channel Decoding (JPCD)

- JRA 1.3.1D on energy efficient probing in CSMA based multi-rate ad hoc networks

- JRA 1.3.2A on advanced MIMO techniques (virtual MIMO, MIMO-FBMC) for low-interference transmission

- JRA 1.3.2B on advanced filtering and adaptive signal processing (OOB, PAPR, SIC)

- JRA 1.3.3A on interference management techniques for heterogeneous networks

- JRA 1.3.3B on game-theoretic energy-efficient control and resource allocation algorithms in heterogeneous networks

- JRA 1.3.3C on self-configuration and optimization of a hybrid LTE Femto - M2M network for smart city applications

- JRA 1.3.3D on Radio resource allocation algorithms in cognitive radio networks with outdated CSI

For each JRA there is a short presentation in section 2 of the report. This analysis includes a description of the activity, an illustration of the adherence to and relevance with the identified fundamental open issues, a short presentation of the main results, and a roadmap for the future joint research. The list of the publications of each JRA is also included in section 2, while a summary list of the main achievements is presented in the introductory section 1.3.

In the Annex, the main technical details of some of the scientific activities that were reported in the previous sections are presented. The emphasis in this section is the presentation of the main results per JRA, along with appropriate references to relevant scientific publications.

Table of Contents

1. Introduction

The role of this WP is to investigate and propose bandwidth and energy efficient techniques at various levels for current and emerging wireless systems and networks. The WP activities include modern wireless network topologies such as multi-tier and Heterogeneous Networks (HetNets). Based on the participants' interests and expertises the WP is divided into three Tasks, each with specific scope and objectives.

Task 1.3.1 "Techniques for power-efficient communications" deals with techniques for power efficiency and minimization at the transceiver and network level.

Task 1.3.2 "Low-interference, low-emission, radio interfaces" deals with the handling of interference by appropriate low interference transmission techniques (e.g. beam-forming, MIMO, GMC).

Task 1.3.3 "Resource Allocation for optimized radio access": is about Radio Resource Management (RRM) and Interference Management (IM) – for a given interference level – in selected scenarios, including HetNets and multi-tier networks.

In this WP, as part of Track 1 of Newcom# project, the research work is concentrated on the algorithmic development of the various WP-relevant solutions. In most cases, although the work is theoretical, practical issues are taken into account by appropriate modelling of the uncertainties of the real world; the goal is always the development of pragmatic solutions applicable to existing (or under development) wireless systems. In various JRAs a connection to Track 2 activities has already been performed and, in some others, it is under current investigation. The goal of these efforts is to apply and test the developed theoretical solutions within real-life conditions with the help of the related expertise of the experimental Newcom# partners.

This report is structured in such a way so as to highlight the main achievements of each JRA. For this purpose, a summary list of the main achievements is presented in the introductory section 1.3, while in section 2 there is a more complete analysis of these achievements for each JRA. This analysis includes a description of the activity, an illustration of the adherence and relevance with the identified fundamental open issues, a short presentation of the main results, a roadmap for the future joint research, and a list of the produced publications. The main technical details of these achievements are reported in the Annex for each JRA. The Annex represents a more detailed presentation of the main results per JRA, along with appropriate references to relevant scientific publications.

1.1 Glossary

3G	Third Generation
3GPP	Third Generation Partnership Project
ABS	Almost Blank Subframe
AGP	Actual GP
AMC	Adaptive Modulation and Coding
ANDSF	Access Network Discovery and Selection Function
AP	Access Point
AWGN	Additive White Gaussian Noise
BAN	Body Area Network
BIC	Bit-Interleaved Coded
BICM	Bit-Interleaved Coded Modulation
BS	Base Station
CAPEX	CAPital EXpenditures
CBR	Constant Bit Rate

CC	Cancellation Carrier
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CESM	Capacity ESM
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CR	Cognitive Radio
CRE	Cell Range Expansion
CSI	Channel State Information
DF	Decode and Forward
DN	Destination Node
DTV	Digital TeleVision
DVB-T	Digital Video Broadcast - Terrestrial
EESM	Exponential ESM
EGP	Expected GP
eICIC	enhanced Inter-Cell Interference Coordination
eNB	evolved Node B
ESM	Effective SNR Mapping
FBMC	FilterBank MultiCarrier
FFR	Fractional Frequency Reuse
GBR	Guaranteed Bit-Rate
GP	GoodPut
GW	GateWay
H2H	Human to Human
HARQ	Hybrid Automatic Repeat Request
HeNB	Home evolved Node B
HetNet	Heterogeneous Network
HetNets	Heterogeneous Networks
HUE	HeNB User Equipment
ICI	Inter Carrier Interference
IC-kESM	Imperfect Channel kESM
IDTV	Integrated Digital TV
IFW	Integrated Femto-Wi-Fi
ISI	Inter Symbol Interference
JPCD	Joint Protocol Channel Decoding
kESM	Cumulant function based ESM
LESM	Logarithmic ESM
LPP	Link Performance Prediction
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
M2M	Machine to Machine
MCD	Measurement Capable Device
MIESM	Mutual Information ESM
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MMSE	Minimum Mean Square Error
MUE	Macrocell User Equipment
NC-OFDM	Non-Contiguous OFDM
OAM	Operations, Administration and Maintenance
OCCS	Optimized Cancellation Carrier(s) Selection
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

OOB	Out Of Band
OP	Optimization Problem
OQAM	Offset QAM
PA	Power Allocation
PAPR	Peak to Average Power Ratio
PDF	Probability Density Function
PER	Packet Error Rate
PF	Proportional Fair
PR	Protection Ratio
PSD	Power Spectral Density
PU	Primary User
QAM	Quadrature Amplitude Modulation
QCI	QoS Class Indicator
QoS	Quality of Service
RA	Resource Allocation
RB	Resource Block
REM	Radio Environmental Map
REM-SA	REM data Storage and Acquisition
RF	Radio Frequency
RN	Relay Node
RSS	Received Signal Strength
SC	Small Cell
SC-FDMA	Single Carrier Frequency Division Multiple Access
SEM	Spectrum Emission Mask
SIC	Successive Interference Cancellation
SINR	Signal to Interference and Noise Ratio
SN	Source Node
SNR	Signal to Noise Radio
SU	Secondary User
TDD	Time Division Duplex
TM	Transmission Mode
TP	Transmission Parameter
TTI	Transmission Time Interval
TV	TeleVision
TVWS	TeleVision White Space
UDP	User Datagram Protocol
UE	User Equipment
USB	Universal Serial Bus
WCDMA	Wideband Code Division Multiple Access
WM	Wireless Microphone
ZF	Zero Forcing

1.2 List of Joint Research Activities (JRAs)

JRA 1.3.1A on resource allocation and scheduling strategies for energy harvesting devices

JRA 1.3.1B on energy-efficient data collection and estimation in wireless sensor networks

JRA 1.3.1C on Joint Protocol Channel Decoding (JPCD)

JRA 1.3.1D on energy efficient probing in CSMA based multi-rate ad hoc networks

JRA 1.3.2A on advanced MIMO techniques (virtual MIMO, MIMO-FBMC) for low-interference transmission

JRA 1.3.2B on advanced filtering and adaptive signal processing (OOB, PAPR, SIC)

JRA 1.3.3A on interference management techniques for heterogeneous networks

JRA 1.3.3B on game-theoretic energy-efficient control and resource allocation algorithms in heterogeneous networks

JRA 1.3.3C on self-configuration and optimization of a hybrid LTE Femto - M2M network for smart city applications

JRA 1.3.3D on Radio resource allocation algorithms in cognitive radio networks with outdated CSI

1.3 Description of the Main WP Achievements in the Reporting Period

This section presents a summary of the main achievements in the reporting period for each JRA in the three Tasks of WP1.3.

1.3.1 Task 1.3.1: Techniques for Power-Efficient Communications

Task leader: Jesus Gomez (CTTC)

In this task various communication strategies and techniques have been developed for multi-user scenarios for which energy efficient operation is mandatory, such as nodes powered from harvesting ambient energy or networks of sensors. This task has also conducted MAC layer optimizations, and developed promising cross-layer techniques such as JPCD. The main results obtained for each of the JRAs in this task are listed below.

- JRA 1.3.1A on resource allocation and scheduling strategies for energy harvesting devices
    - Development of optimal strategies to recharge the batteries wirelessly in order to prolong the network lifetime while maximizing the sum rate have been proposed for multiuser MIMO networks
    - Design of a procedure for switching on and off BSs solely powered with an energy harvesting source (e.g., solar panels) and a finite battery, in order to reduce around 15-20% the size of the solar panels and the batteries.
    - Proposal of user association strategies to achieve load balancing in heterogeneous networks where the BSs were solely powered with finite batteries and energy harvesting sources that allowed the BSs to recharge their batteries.
- JRA 1.3.1B on energy-efficient data collection and estimation in wireless sensor networks
    - Work on distributed in-network reconstruction of sparse signals. Proposal of a decentralized scheme, referred to as Distributed iterative Thresholding (DiT). The convergence of the corresponding algorithms has also been studied.
    - Design of distributed algorithms for the characterization of non-asymptotic confidence region in sensor networks. A variant of the sign-perturbed-sum algorithm by Campi et al. has been proposed.
    - Development of an iterative algorithm for outlier detection in wireless sensor networks. The algorithm proposed is able to isolate more than 30% of sensors providing outliers. The equilibrium properties and dynamics of the algorithm are studied.
- JRA 1.3.1C on Joint Protocol Channel Decoding (JPCD)
    - Joint protocol-channel decoding techniques have been developed to improve the estimation quality of the type of a packet corrupted by transmission errors. Optimal and a suboptimal estimation algorithms have been developed.
- JRA 1.3.1D on energy efficient probing in CSMA based multi-rate ad hoc networks

  - Design of a cross-layer energy optimum adaptive modulation and coding policy which improves energy consumption significantly compared to a single-layer policy.
  - Design of a cross-layer selection of transmission capacity and MAC layer attempt rate for an ALOHA underwater acoustic network. The proposed joint allocation reduces the energy consumption by allocating a higher MAC capacity but a lower physical layer capacity to nodes which have a greater distance to the base station.

1.3.2 Task 1.3.2: Low-interference, low-emission, radio interfaces

Task Leader: Adrian Kliks (PUT)

The main goal of this Task is to propose solutions for future wireless communication systems that would lead to an efficient use of resources (e.g., energy, assigned spectrum) and to the minimization of the interference induced to neighboring systems. In the first JRA, the problem of energy-efficient communications for body area networks (BAN) is considered together with the application of a very efficient FBMC technique for out-of-band emission minimization. In the second JRA, the problem of non-linearities in the context of non-contiguous systems is considered, concentrating on the out-of-band emission reduction techniques. The main achievements are listed below:

- JRA 1.3.2A on advanced MIMO techniques (virtual MIMO, MIMO-FBMC) for low-interference transmission
  - The detailed derivation of the impact of the precoding applied to the MIMO-FBMC scheme on the average transmit power has been obtained; the results of this work has been published in a joint Journal paper.
  - A new algorithm for multi-user scheduling utilizing application of FBMC modulation in MIMO systems has been proposed. MIMO schemes have been also investigated in the context of body area networks.The efficiency of the novel solution has been verified by computer simulations. In particular, the BAN has been treated as an ad-hoc MIMO system that can be utilized for improvement of regular connection between the user and the distant access point.
- JRA 1.3.2B on advanced filtering and adaptive signal processing (OOB, PAPR, SIC)
  - The main effort has been put on the derivation of advanced and computationally efficient solutions for the reduction of out-of-band emission in the non-contiguous transmission scenario. The analysis of the PAPR characteristics in such systems has been also provided.

1.3.3 Task 1.3.3: Resource Allocation for optimized radio access

Task Leader: Luca Sanguinetti (CNIT)

This Task targets the development of energy-efficient algorithmic solutions for the management of resources and for controlling interference in wireless networks. Special emphasis is given to HetNet topologies (including relaying nodes, stationary and mobile nodes, femtocells, picocells, and others) in different operating conditions and scenarios. This is achieved by using analytical tools provided by network control theory, game theory as well as other mathematical theories specifically tailored to the development, study and analysis of distributed algorithmic solutions. The Task consists of four JRAs, and the main achievements are listed below:

- JRA 1.3.3A on interference management techniques for heterogeneous networks
  - A REM-based architectural framework has been proposed for supporting interference management techniques in HetNets including both LTE and Wi-Fi

technologies. It consists of general layered architecture that considers the inclusion of global and local REM databases at different nodes of the network.
    - A neighborhood cooperation algorithm for deciding the TVWS spectrum assignment to small cells has been proposed and evaluated.
    - In conjunction with JRA#G in WP2.1, the computation of the maximum allowed transmit power so as not to interfere with TV receivers when TVWS are allocated to small cells has been carried out based on real measurements performed in an indoor building.
    - An interference coordination scheme for HetNets that jointly exploits the frequency, power and time dimensions has been proposed and assessed.
- JRA 1.3.3B on game-theoretic energy-efficient control and resource allocation algorithms in heterogeneous networks
    - A distributed power allocation scheme has been proposed for energy-aware, non-cooperative wireless users with minimum-rate constraints in the uplink of a multicarrier heterogeneous network.
    - A non-cooperative game has been formulated modelling the power allocation problem that arises in a heterogeneous multipoint-to-multipoint network wherein each transmitter and receiver pair can arbitrarily choose whether to selfishly maximize its own spectral or energy efficiency.
    - Proposal of an iterative and distributed algorithm inspired by best response dynamics in which (at each step) every transmitter updates its power exploiting a local estimate of its current SINR at the receiver. The performance of the proposed solution has been evaluated by means of numerical results in the uplink of a small cell network.
- JRA 1.3.3C on self-configuration and optimization of a hybrid LTE Femto - M2M network for smart city applications
    - Evaluation of M2M Scheduling Opportunities in a LTE Small Cell Network for Smart City Applications.
    - Definition of a Mixed Integer Linear Programming (MILP) model for the LTE Uplink radio resource assignment problem.
- JRA 1.3.3D on Radio resource allocation algorithms in cognitive radio networks with outdated CSI
    - Development of a new RA technique for CR BIC-OFDM systems with outdated CSI, which exploits a Link Performance Prediction (LPP) scheme based on the κ ESM technique.
    - Extension of the scenario to the case of a generic number of decode-and-forward relay nodes for a dual-hop transmission (source-relay-destination). A “best relay” selection mechanism is defined, exploiting the goodput metric. A new objective function for the resource allocation (RA) problem is formulated that considers the total PER for the source-relay-destination transmission.
    - Derivation of an enhanced RA technique, suitable to a realistic scenario, where only imperfect CSI is available at the transmitter for a dual-hop transmission. In this scenario, a new channel prediction model is exploited in the LPP κ ESM technique.

2. Detailed Activity and Achieved Results

In this section, a summary of the research work in each JRA is provided. More specifically, for each JRA there is the description of the objectives, of the scenarios of investigation, and possible of relations to others JRAs of both Track 1 and Track 2. Furthermore, there is a sub-section on the relevance with the identified fundamental open issues, which aims to identify the connection with the previous deliverable (D13.1) and to present the addressed challenges/open issues. In the main results and planned activities sub-section, a summary of the main results of each JRA is presented, along with a roadmap for the joint research work of the next (final) year. Finally, there is a sub-section with all the Newcom# publications related to each JRA.

2.1 JRA 1.3.1A on resource allocation and scheduling strategies for energy harvesting devices

Leader: Javier Rubio (UPC)

Researchers involved: Javier Rubio, Antonio Pascual Iserte (UPC), Maria Gregori, Miquel Payaró (CTTC)

2.1.1 Description of Activity

The purpose of the JRA is to develop transmission strategies such as resource allocation, scheduling, etc., in networks where either the transmitter or the receivers are energy-constrained and are provided with energy harvesting sources that are capable to produce sustainable networks from the energy point of view. Within this framework, we have studied different scenarios of interest and relevant results have been obtained. The description of the activities performed during the last year is explained chronologically.

First, we studied the framework of simultaneous transmission of information and power from the transmitter to the receivers in order for the receivers to use the received radio frequency (RF) power to recharge the battery. In this broadcast scenario, the transmitter designed its resource allocation strategy considering two different sets of receivers: a set of receivers willing to receive data and a set of receivers willing to receive power through RF transmission to recharge the batteries.

Strategies to dynamically switch off and switch on transmitters whenever the traffic is low in order to reduce the energy consumption have also been studied. The transmitter was considered to be solely powered by an energy harvesting source and a finite battery. The dimensioning of the energy units (battery, solar panels) was also covered.

Another scenario that has been considered is the case where there are multiple transmitter-receiver pairs (users) where the transmitters are able to harvest energy from RF signals generated by their neighbors and also from a fixed energy-harvesting source. In this setup, the transmission strategy that achieves the Nash equilibrium of the network in terms of rate is investigated by taking into account the interference and energy harvesting that occurs across the different users.

We have also studied the problem of QoS-oriented temporal and spatial user scheduling mechanisms in multiuser MIMO wireless networks where the terminals are battery-limited devices provided with energy harvesting sources. The idea was to design strategies that considered such battery-related aspects and, thus, improved the performance (data rate obtained) when compared with traditional strategies that did not consider energy limitations.

Finally, user association in multi-tier networks for balancing the traffic load (and, thus, achieve higher network throughput) have been addressed. In such scenario, the transmitters are only powered by energy harvesting sources.

Along with the research presented previously, we have also carried out some joint activities with a JRA from Track 2. More specific, we have studied the energy modeling and profiling of a physical layer of a modern wireless communications system [3]. Hardware implementation of an interference mitigation technique for LTE systems has also been addressed among participants of Track 1 and Track 2 [13]. The outcomes of all these activities are reported in a series of publications (see section 2.1.4).

2.1.2 Relevance with the identified fundamental open issues

The research carried out during the last 12 months has covered and addressed some of the identified open issues that we presented at the previous deliverable (D13.1) and also has initiated the study in new open issues that have been encountered and found interesting during the research process.

One of the first open issues that we identified is the need for more elaborated energy consumption models. In the literature, researchers just consider very simplistic models only focusing on the radiated power and a fixed consumption due to equipment. We have generalized the power consumption models usually found in the literature by considering different energy sinks that appear in real systems. A journal paper is expected to appear soon.

We also mentioned the idea of generalizing the multiuser network where the transmitter was energy-constrained by considering multiple nodes. To the best of our knowledge, a network with just one transmitter and a few receivers had been studied at that time. In [5] we presented a resource allocation strategy based on variational inequalities for a multiuser network with multiple transmitter-receiver pairs where the transmitters were energy-constrained provided with energy harvesting sources.

User scheduling policies in networks where the receivers are energy-constrained was another open issue that we identified. We have addressed such scheduling issues and the relevant results can be found in [2].

Additionally, some of the open fundamental issues presented in the previous deliverable are currently being addressed and others are still pending for future research. Moreover, some new fundamental open issues have been studied as they have been found during the course of the research. For example, strategies for switching on and off transmitters that are powered with a finite battery and provided with an energy-harvesting source have been designed (see [6]). Finally, user association strategies in multi-tier networks where the transmitters are energy-constrained with the goal of achieving load balancing in the network have been studied. Partial results are presented in [1] and a journal paper is under development.

2.1.3 Main Results Achieved in the Reporting Period and planned activities

The results obtained in the reporting period for the different target scenarios will be presented in section 4.1 of the appendix of this document. In general, we can conclude that whenever we have information and control the energy that is being used, we can design strategies that provide longer lifetime in terms of longer battery durability. Also the network throughput can be enhanced at the same time depending on the energy capabilities.

In terms of planned activities for the last year, we can define the following research areas:

- Scheduling policies in networks where simultaneous information and energy from the transmitter to the receivers is allowed.
- Extension of the load balancing techniques discussed before considering stochastic optimization techniques.
- Extension of the scenario where the transmitters are able to switch on/off to the case where the transmitters are able to adjust its coverage area pattern. This adjustment

could be carried out considering dynamic learning techniques or big-data approaches to make the decision.

2.1.4 Publications

[1] J. Rubio, A. Pascual Iserte, J. Del Olmo and J. Vidal, " User Association for Load Balancing in Heterogeneous Networks Powered with Energy Harvesting Sources", IEEE Globecom 2014, Austin, USA, December 2014.

[2] J. Rubio and A. Pascual Iserte, "Energy-Aware User Scheduling for Downlink Multiuser-MIMO Systems", IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, September 2014.

[3] N. Bartzoudis, O. Font Bach, M. Payaro, A. Pascual Iserte, J. Rubio, J. J. Garcia Fernandez and A. Garcia Armada, "Energy Profiling of FPGA-Based PHY-Layer Building Blocks Encountered in Modern Wireless Communication Systems", IEEE Sensor Array and Multichannel Signal Processing Workshop, A Coruña, Spain June 2014. [JOINT WITH TRACK 2]

[4] O. Font Bach, N. Bartzoudis, M. Payaro and A. Pascual Iserte, "Measuring the Performance of a Distributed Interference Management Scheme in a LTE-Based HetNet Deployment", IEEE Sensor Array and Multichannel Signal Processing Workshop, A Coruña, Spain June 2014. [JOINT WITH TRACK 2]

[5] M. Gregori, M. Payaró, “Multiuser communications with energy harvesting transmitters“, IEEE ICC 2014 -Wireless Communications Symposium ('ICC'14 WCS'), June 2014.

[6] J. Rubio, A. Pascual Iserte, J. Del Olmo and J. Vidal, "Dynamic Base Station Switch On/Off Strategies for Sustainable Wireless Networks", IEEE International Workshop on Signal Processing Advances for Wireless Communications, Toronto, Canada June 2014.

[7] J. Rubio, A. Pascual Iserte, J. J. Garcia Fernandez, A. Garcia Armada, O. Font Bach and N. Bartzoudis, "Asymptotic Analysis of Multiuser-MIMO Networks with Battery-Constrained Receivers", European Wireless, Barcelona, Spain May 2014, pp. 1004 - 1009. [JOINT WITH TRACK 2]

[8] J. J. Garcia Fernandez, A. Garcia Armada, J. Rubio, A. Pascual Iserte, O. Font Bach and N. Bartzoudis, "Adaptive Block Diagonalization and User Scheduling with Out of Cluster Interference", European Wireless, Barcelona, Spain May 2014, pp. 238 - 243. [JOINT WITH TRACK 2]

[9] J. Rubio, A. Pascual-Iserte, “Energy-Aware Broadcast MU-MIMO Precoder Design with Imperfect Channel and Battery Knowledge”. IEEE Transactions on Wireless Communications, April 2014.

[10] O. Font-Bach, N. Bartzoudis, A. Pascual-Iserte, M. Payaró, L. Blanco, D. López Bueno and M. Molina, "Interference Management in LTE-based HetNets: a Practical Approach", Transactions on Emerging Telecommunications Technologies, April 2014. [JOINT WITH TRACK 2]

[11] J. Rubio, A. Pascual-Iserte, “Energy-Aware Broadcast MU-MIMO Precoder Design with Imperfect Battery Knowledge”. Globecom 2013 (IEEE Global Communications Conference). Atlanta (USA), December 2013.

[12] J. Rubio, A. Pascual-Iserte, “Simultaneous Wireless Information and Power Transfer in Multiuser MIMO Systems”. Globecom 2013 (IEEE Global Communications Conference). Atlanta (USA), December 2013.

[13] O. Font-Bach, N. Bartzoudis, M. Payaró, A. Pascual-Iserte, “Hardware-Efficient Implementation of a Femtocell/Macrocell Interference-Mitigation Technique for High-Performance LTE-Based Systems”. Proceedings FPL 2013 (23rd International

Conference on Fielf Programmable Logic and Applications), pp. 1-4, ISBN 978-1-4799-0004-6. Porto (Portugal), September 2013. [JOINT WITH TRACK 2]

2.2 JRA 1.3.1B on energy-efficient data collection and estimation in wireless sensor networks

Leader: Francesca Bassi (CNRS/UPS)

Researchers involved: Michel Kieffer, Francesca Bassi, Wenjie Li (CNRS-UniPS), Davide Dardari, Vincenzo Zambianchi, Gianni Pasolini (CNIT-UniBo), Sophie Fosson, Enrico Magli (CNIT-PoliTo), Javier Matamoros, Carles Anton-Haro (CTTC).

This JRA is a cross work package JRA that belongs to WP 1.2 and WP 1.3. Therefore, for the sake of completeness, some of the information will be duplicated in the respective deliverables.

2.2.1 Description of Activity

In this JRA we consider the reference scenario of a wireless sensor network, composed by several autonomous nodes, able to communicate via the wireless channel. Each node independently collects measurements of a physical quantity. The network needs to compute some function of the whole set of measurements, in order to accomplish some task (e.g. temperature monitoring, fire alert, intrusion detection).

In this context, the JRA focuses on the design and analysis of distributed network architectures able to contain the energetic expenditure of the network, essentially by restraining the amount of data the nodes need to exchange. This goal can be achieved by acting at different levels. During the reporting period the activity of the JRA has focused on the signal acquisition process (reduction of the data to be acquired is obtained leveraging on compressed sensing principles), the information diffusion strategy (competing strategies as consensus algorithm and smart flooding have been compared in structured and unstructured network topologies) and the distributed signal processing algorithm (a fully distributed confidence region computation algorithm has been proposed). The design of a distributed fault detection solution has been contributed as well.

The activity has revolved around the following research visits between the partner institutions.

- Research visit: Sophie Fosson (CNIT-PoliTo) to CTTC
  - Dates: June 14th, 2013 – July 14th, 2014.
  - Title: Distributed sparse signal estimation: new models and solutions.
  - Funding: funded by the Newcom# Mobility Grant program.
- Research visit: Vincenzo Zambianchi (CNIT-UniBo) to CNRS-UniPS
  - Dates: November 7th, 2013 – May 7th, 2014.
  - Title: Distributed field estimation via consensus techniques.
  - Funding: partially funded by the Newcom# Mobility Grant program.
- Research visit: Wenjie Li (CNRS-UniPS) to CNIT-UniBo
  - Dates: May, 10th – July, 27th 2014 and September 11th – October 31st, 2014
  - Title: Distributed outlier detection in wireless sensor networks
  - Funding: funded by the Newcom# Mobility Grant program.

2.2.2 Relevance with the identified fundamental open issues

During the reporting period the joint activity of S. Fosson, E. Magli (CNIT-PoliTo), and J. Matamoros, C. Antón-Haro has been devoted to the problem of the distributed detection of signals with sparse and common support from the network measurements. This is in adherence with the identified open issue 6 of the relevant section of the previous deliverable

(D13.1) (possibility to distribute compressive sensing techniques to enable signal acquisition in wireless sensor networks).

The joint activity of V. Zambianchi, D. Dardari, G. Pasolini (CNIT-UniBo), and M. Kieffer, F. Bassi (CNRS-UPS) has been devoted to the study of the efficiency of consensus algorithms for information dissemination in the network, when the problem is the estimation of a parameter vector from the set of all measurements. This is in adherence with the identified open issue 3 (energetic efficiency of distributed data dissemination strategies).

The joint activity of W. Li, M. Kieffer, F. Bassi (CNRS-UPS), and D. Dardari, G. Pasolini (CNIT-UniBo), and has been devoted to the study of distributed outlier/fault detection in wireless sensor networks. This is in adherence with the identified open issue 7 (robustness against sensor failure).

2.2.3 Main Results Achieved in the Reporting Period and planned activities

The joint work of CTTC and CNIT-PoliTo on signal support detection is detailed in the Annex in sections 4.2. It has been partly presented at the ICASSP 2014 conference, in Florence. The work on distributed ADMM algorithms for in-network reconstruction of sparse signals has been partly submitted to GlobalSIP'14. A journal paper is in preparation.

CNRS-UPS and CNIT-UniBo work on distributed algorithms for the characterization of non-asymptotic confidence region in sensor networks. A variant of the sign-perturbed-sum algorithm by Campi et al. has been proposed. Three data collection strategies adapted to the distributed SPS algorithm are compared theoretically and experimentally. These results are detailed in the Annex. This work has been partly presented at the EuCNC 2014 conference in Bologna. A journal paper has been submitted.

CNRS-UPS and CNIT-UniBo work on outlier detection in wireless sensor networks. An iterative algorithm is proposed able to isolate more than 30% of sensors providing outliers. The equilibrium properties and dynamics of the algorithm are studied. This is detailed in the Annex section 4.4. A journal and a conference paper are in preparation. The next step is to evaluate the proposed technique in the context of the DATASENS platform (joint activity with Track 2).

2.2.4 Publications

[1] Distributed support detection on jointly sparse signals, S. Fosson (CNIT/PoliTo), J. Matamoros (CTTC), C. Antón-Haro (CTTC), E. Magli (CNIT/PoliTo), IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Florence, Italy, May 2014, pp 6434 - 6438

[2] Distributed SPS Algorithms for Non-Asymptotic Confidence Region Evaluation, V. Zambianchi (CNIT-UniBo), M. Keffer (CNRS-UPS), F. Bassi (CNRS-UPS), G. Pasolini (CNIT-UniBo), D. Dardari (CNIT-UniBo), European Conference on Networks and Communications (EuCNC), Bologna, Italy, June 2014, pp 1 – 5.

[3] J.Matamoros, S.Fosson, E.Magli, C. Antón-Haro, Distributed ADMM for in-network reconstruction of sparse signals with innovations, submitted to IEEE Global Conference on Signal and Information Processing (GlobalSIP).

[4] F. Bassi, A. Fraysse, E. Dupraz, M. Kieffer. Rate-distortion bounds for Wyner-Ziv coding with Gaussian scale mixture correlation noise, to appear in IEEE transactions on Information Theory, 2014.

Submitted:

[5] W. Li, F. Bassi, M. Kieffer. Robust Bayesian compressed sensing over finite fields: asymptotic performance analysis, submitted to IEEE transactions on Information Theory, 2014.

[6] J. Matamoros, S. Fosson, E. Magli, C. Antón-Haro, Distributed ADMM for in-network reconstruction of sparse signals with innovations, submitted to IEEE Global Conference on Signal and Information Processing (GlobalSIP).

[7] V. Zambianchi, M. Kieffer, G. Pasolini, D. Dardari, F. Bassi, Efficient distributed confidence region characterization over wireless sensor networks, submitted in IEEE trans. on Wireless Communications, 2014.

2.3 JRA 1.3.1C on Joint Protocol Channel Decoding (JPCD)

Leader: Michel Kieffer (CNRS)

Researchers involved: N. Barbot, M. Kieffer (CNRS/UniPS), M. Chiani, E. Paolini, M. Mazzotti (CNIT-UniBo)

2.3.1 Description of Activity

The aim of this JRA is to exploit all information available at upper layers of the protocol stack to improve processing at lower layers, such as synchronization, channel estimation, channel decoding, or robust header recovery. Several results on JPCD have already been obtained in the context of Wi-Fi. Our aim is to extend these results to LTE, LTE-A, and address new issues raised by these communication techniques. Some of the obtained results are planned to be translated to OpenAirInterface within WP 2.3: Flexible communication terminals and networks.

Within this JRA, two activities were performed. The first is devoted to the robust decoding of ROHC-encoded packets. Robust header recovery techniques have been extended to the case of compressed headers and presented in an ICASSP 2014 paper. The second activity is related to the reliable packet type estimation. In previous JPCD papers, the type of the packet to decode was assumed perfectly known. The knowledge was coming from previous handshaking steps. We now proposed MAP estimators to determine the type of packets by verifying the global consistency of the packet structure instead of the presence of few bits used to indicate the type of the packet.

2.3.2 Relevance with the identified fundamental open issues

Reliable decoding of ROHC-encoded packets is related to Open Issue 1 of the relevant section in the previous deliverable. The main difficulty comes from the fact that the residual redundancy in ROHC-encoded packets is significantly reduced compared to a situation where plain headers are transmitted.

Reliable packet type identification is linked to Open Issue 3. As mentioned in Deliverable D1.3.1, first results on robust header recovery assumed that the packet structure is perfectly known. This is very useful to identify fields which content is known prior to reception. When the packet type is not known, it has to be estimated first in a reliable way.

2.3.3 Main Results Achieved in the Reporting Period and planned activities

Joint protocol-channel decoding techniques have been developed to improve the estimation quality of the type of a packet corrupted by transmission errors. It exploits the redundancy present in the protocol stack to determine the packet type which is the most probable a posteriori. Two optimal and a suboptimal estimation algorithms were presented. The latter is illustrated on the type estimation of packets compressed with the Robust Header Compression algorithm in unidirectional mode. Compared to a classical packet type estimation technique, improvements of more than 3.9 dB are observed in terms of channel SNR at header error rates of 10^{-2}.

2.3.4 Publications

[1] W. Kai, L. Jinghui, M. Kieffer, and P. Duhamel, Reliable packet type estimation via joint protocol-channel decoding, Proc. ICASSP 2014, pp. 1921 – 1925, 2014.

2.4 JRA 1.3.1D on energy efficient probing in CSMA based multi-rate ad hoc networks

Leader: Mehmet Koseoglu (BILKENT)

Researchers involved: Mehmet Koseoglu, Ezhan Karasan (BILKENT), Lin Chen (CNRS/UPSUD)

2.4.1 Description of Activity

In the first joint study between BILKENT and CNRS/UPSUD, we have designed a cross-layer adaptive modulation and coding scheme which minimizes the energy consumption in a CSMA-based wireless network. To make switching decisions between different modulation and coding rate schemes, previous studies proposed policies which only consider physical layer information such as bit error rate or packet loss rate. However, this approach fails to optimize energy consumption which significantly depend on the MAC-layer state and parameters. We propose a cross-layer switching policy which jointly considers PHY and MAC layers and optimizes the energy efficiency for a CSMA-based wireless network. We have evaluated this policy for pedestrian and vehicular channel models and showed that the proposed policies significantly outperform an optimum single-layer policy that considers only physical layer performance.

In another recently started joint study, we investigate the energy efficiency of an ALOHA-based underwater acoustic network. Underwater networks suffer from energy efficiency challenges due to difficulties in recharging underwater nodes. Besides, underwater acoustic networks show unique transmission characteristics such as frequency dependent attenuation that causes the transmission power to significantly depend on the bandwidth and the distance. In this joint study, we investigate the energy minimization problem in underwater ALOHA networks considering the unique transmission properties of the underwater medium. We first formulate a MAC-layer energy optimization problem where the nodes are assumed identical in terms of physical layer parameters such as distance and transmission power. We analytically obtain the energy-optimum attempt rate for ALOHA which minimizes the energy consumption per successfully transmitted bit. We then investigate the cross-layer selection of transmission capacity and MAC layer attempt rate for an ALOHA network. Our results show that such cross-layer optimization reduces the energy consumption per bit in comparison to separate optimization of both layers.

2.4.2 Relevance with the identified fundamental open issues

As mentioned in Deliverable D13.1 Sec. 2.1.4.1 (a), one of the fundamental issues regarding wireless networks is to reduce energy consumption. To improve the battery lifetimes of wireless devices and due to environmental considerations, it is widely agreed that the energy efficiency of wireless communication protocols has to be improved. There are many wireless communications protocols that employ a variant of the carrier sense multiple access protocol (CSMA) due to its simple and distributed nature (e.g., the IEEE 802.11 for WLANs, IEEE 802.15.4 for WPANs and B-MAC for sensor networks. In the literature most of the energy efficiency studies are confined to a specific standard and also they employ a single-layer approach as mentioned in Sec. 2.1.4.1 (b-c). To address these fundamental open issues, in this JRA, we tackle the energy efficiency problem in wireless networks using a cross-layer. approach.

Although not explicitly mentioned in the DOW of the NoE, underwater networks are also strictly energy-constrained as it is challenging to recharge the underwater nodes. For that reason, we also develop cross-layer techniques to minimize energy consumption in underwater networks.

2.4.3 Main Results Achieved in the Reporting Period and planned activities

In the first joint study, we proposed a cross-layer energy optimum adaptive modulation and coding policy which improves energy consumption significantly compared to a single-layer policy. We have investigated the effect of various parameters on the energy efficiency of a CSMA based wireless network such as network congestion, power consumption profile of the hardware, packet lengths.

In the second joint study, we investigated the cross-layer selection of transmission capacity and MAC layer attempt rate for an ALOHA underwater acoustic network. The proposed joint allocation reduces the energy consumption by allocating a higher MAC capacity but a lower physical layer capacity to nodes which have a greater distance to the base station.

Details of the technical achievements of both studies can be seen in section 4.5 in the Appendix.

In the immediate future, we plan to finish the publication of the results of the first joint study. We will then focus on the second joint study which considers the energy efficiency of underwater acoustic networks. We have already prepared a manuscript on this topic and plan to finalize and submit the manuscript in the next reporting period.

2.4.4 Publications

[1] M. Koseoglu, E. Karasan and L.Chen, “Energy-efficient Adaptive Modulation and Coding for CSMA Networks,” submitted to IEEE Transactions on Vehicular Technology.
[2] M. Koseoglu and E. Karasan, “Energy-optimum Throughput and Carrier Sensing Rate in CSMA-based Wireless Networks,” IEEE Transactions on Mobile Computing, vol.13, no.6, June 2014.
[3] M. Koseoglu and E. Karasan, “Spatio-Temporal Analysis of Throughput for Single-Hop CSMA Networks,” IEEE Communications Letters, vol. 18, no. 4, pp. 564-567, April 2014.
[4] M. Koseoglu and E. Karasan, "Energy-optimum Throughput and Carrier Sensing Rate in CSMA-based Wireless Networks", Aselsan Inc. Telecommunications Workshop, Nov. 2013.

2.5 JRA 1.3.2A on advanced MIMO techniques (virtual MIMO, MIMO-FBMC) for low-interference transmission

Leader: Adrian Kliks (PUT)

Researchers involved: Adrian Kliks, Paweł Kryszkiewicz, Hanna Bogucka (PUT), Màrius Caus, Ana I. Pérez Neira (UPC), Michał Maćkowiak, Marko Beko, Carla Oliveira, Luis Correia (INOV), Marco Moretti (CNIT/UniPi)

2.5.1 Description of Activity

According to the DoW the main aim of this JRA is the joint work on advanced MIMO techniques for low-emission and low-interference systems. The realization of this strategic goal has been achieved in two ways. First, as the continuation of the activities initiated in the first project year, the application of the MIMO-OFDM concept with distributed antenna subsystem (and virtual MIMO) in the Body Area Networks was analyzed in details. Second, the impact of the selected pre-processing algorithms on the characteristics of the transmitted signal in MIMO-FBMC has been analyzed, followed by the development of the multi-user scheduling algorithm in the scenarios where users utilize the aforementioned modulation scheme. According to the plans proposed in the first year, these two paths led to the achievement of the same target, i.e., it is highly considered to propose the sophisticated algorithms for MIMO-OFDM/FMBC schemes in various contexts including application in Body Area Networks.

2.5.2 Relevance with the identified fundamental open issues

Various fundamental open issues identified in the previous deliverable (D13.1) have been considered in this JRA. First, various algorithms for MIMO-FBMC systems have been tested. Various precoding schemes have been developed so far for the OFDM systems, proving the advantages of MIMO schemes. Although some work has been already done towards application of these techniques for FBMC systems, many of them are still to be tested in real systems. It can be stated that one of the critical topics is the impact of precoding on the average transmitted power. The goal of our study is to verify how various precoding techniques influence the transmit signal in terms of energy efficiency and transmit power characteristics. Even if uncontrolled transmit power variations caused by the precoding algorithms could potentially lead to interference increase, the use of transmit precoding strategies in the FBMC context has been proved to be useful to avoid ICI and ISI. However, the impact of precoding on the average transmitted power is still an open issue.

Another open issue identified in this JRA deals with the application of energy efficient solutions for wireless Body Area Networks. In that context, efficient channel modeling is crucial for the proper evaluation of various proposed algorithms. From the point of view of interference management, each of the nodes can be treated as the one aerial in some virtual MIMO system, thus procedures from classical MIMO systems could be applied. However, this issue still requires lots of work. For example, an open point is to verify the efficiency of several algorithms used for LTE networks in the context of virtual MIMO BAN systems.

Also the application of multicarrier modulation formats for wireless BANs is an interesting area of research. Although on-body sensors usually require low-power transmission, recent achievements in that area have identified new scenarios where OFDM and FBMC schemes could be applied.

2.5.3 Main Results Achieved in the Reporting Period and planned activities

One of the considered schemes during the reporting period assumes the presence of the advanced Body Area Network, which will be used to support the “regular” transmission, i.e., the cell-phone connection between the mobile user and the remote access point. In the proposed solution, the sophisticated network deployed on user body (e.g. based on the recently proposed textile antennas) cooperates with the user mobile device improving the performance of the connection by benefiting of the advantages of MIMO-OFDM transmission schemes. Such a scenario can be easily illustrated in the military context, where soldiers are equipped with advanced and smart clothes. In the considered case study, the external clothes are used for creation of the ad-hoc MIMO scheme, since the physical distances between the antennas mounted on-body can be high compared to the applied wavelength. For such a scheme the joint bit-and-power loading algorithm applied for MIMO-OFDM scheme with transmit antenna selection approach have been considered. The extensive computer simulations have proved the correctness of the approach, since much gain can be achieved in relation to the case where only the SISO connection will be kept. One can however immediately notice a great variety of technical problems that have to be solved, such as power delivery to aerials, synchronization, coordination etc. Thus, the plans related to this activity assume the consideration of more technical limitations and constraints, along with the application of advances processing schemes, such as FBMC technique. The related results have been presented at the IEEE ISWCS 2014 conference.

In parallel, the in-depth analysis of the impact of precoders on the characteristics of transmit signal in MIMO-FBMC schemes has been studied. In particular, the closed form formulas for the ZF and MMSE precoders that describe the influence of the precoders on the transmit signal have been derived and verified by simulation,. The results of this activity have been accepted and published in one of the leading international journals.

Furthermore, the advantages of the FBMC modulation schemes have been further studied in the context of multi-user scheduling scenario. Detailed algorithm for user scheduling has been proposed that takes into account the interference induced between the users. The results of this work have been also published at the aforementioned IEEE ISWCS conference.

Detailed results have been presented in appendix sections 4.6 and 4.7. The following activities have been identified for the future work:

- Continuation of the work on efficient multi-user scheduling techniques for MIMO-FMBC schemes
- As the extension of the already finished work (i.e. derivation of the relation between the precoders used in the system and the average transmit power) the analysis of the OOB emission in the analogous context will be considered.

2.5.4 Publications

[1] Michal Mackowiak, Luis Correia, Adrian Kliks, Paweł Kryszkiewicz, "MIMO Channel Analysis in the Context of Body Area Networks" , in Proceedings of the 11th International Symposium on Wireless Communication Systems (ISWCS 2014), 26-29 August 2014.

[2] Màrius Caus, Ana I. Pérez Neira, Adrian Kliks, Characterization of the effects of multi-tap filtering on FBMC/OQAM systems , EURASIP Journal on Advances in Signal Processing, Vol. 2014, 2014.

[3] Màrius Caus, Ana I. Pérez Neira, and Marco Moretti, "SDMA for FBMC with block diagonalization," in *Signal Processing Advances in Wireless Communications (SPAWC), IEEE 14th International Workshop on*, 2013.

[4] Màrius Caus, Ana I. Pérez Neira, Marco Moretti, Adrian Kliks, "A margin adaptive scheduling algorithm for FBMC/OQAM systems" , in Proceedings of the 11th International Symposium on Wireless Communication Systems (ISWCS 2014), 26-29 August 2014.

2.6 JRA 1.3.2B on advanced filtering and adaptive signal processing (OOB, PAPR, SIC)

Leader: Pawel Kryszkiewicz (PUT)

Researchers involved: Adrian Kliks, Paweł Kryszkiewicz, Hanna Bogucka, Krzysztof Cichoń (PUT), Yves Louet, Amor Nafka (CNRS/SUPELEC)

2.6.1 Description of Activity

This JRA focuses on the development of advanced filtering and signal processing schemes that aims at improving the performance of twireless communication links, focusing on energy efficiency. The problem of effective users' coexistence (also in crowded environments) is of very high importance and leads to the definition of specific requirements on future wireless networks, such as low out-of-band emission and efficient energy utilization. In that context, there is a need for the investigation of sophisticated solutions aiming at minimizing the unwanted signal emissions out of the nominal band, therefore reducing at the same time the interference induced to the neighboring users. Within this JRA an adaptive precoding technique for Non Contiguous OFDM (NC-OFDM) modulation has been proposed that lowers the amount of power radiated out of band.

Another research aspect considered in this joint activity area is the analysis of the PAPR metric from the perspective of non-contiguous transmission. In such a scheme only a small subset of subcarriers in a multicarrier symbol (such as OFDM or FBMC) is deactivated, allowing for parallel transmission of primary (licensed, and in this case narrowband) and secondary (non-licensed, wideband) signal. The problem of PAPR characteristic in such scenario has not been addressed in details so far. The work initiated in the previous year tries to fill this niche.

There is a direct connection between this activity and Track 2, since the algorithms derived for out of band radiation reduction (presented in the previous year) are considered for hardware implementation within WP2.1.

2.6.2 Relevance with the identified fundamental open issues

Following the open issues identified and presented in the previous deliverable (D13.1) it can be highlighted that the problem of high PAPR coefficients is significant for guaranteeing high efficiency of power amplifier and low interference emission. The development of hardware efficient PAPR reduction methods still needs to be addressed. Moreover, it can be easily verified that PAPR analysis and algorithms have been usually designed for OFDM systems. Further work is needed to adapt those solutions to non-contiguous multicarrier systems. The non-contiguous transmission schemes require extremely high attenuation of the unwanted emissions in the unused subbands. The development of hardware efficient solutions is critical.

2.6.3 Main Results Achieved in the Reporting Period and planned activities

One of the results achieved in this JRA is the development of advanced spectrum shaping methods for NC-OFDM transmitter, which is an extension of the previously proposed Cancellation Carriers (CC) based method that aim at reducing subcarriers sidelobes power in the Out-of-Band (OOB) region. It was observed that wider view to this problem is required as the aim should not be just to reduce OOB radiation in general, but to reduce the effective interference power in the Primary User (PU) receiver. Such a modification allowed for improved protection of PU while limiting power required by CCs. Additionally, a modification decreasing the complexity of CCs calculation was proposed. The interference minimizing schemes, of which one was characterized by low complexity, were reported in conference publications (i.e. one Polish conference paper and one international conference paper).

The second main result achieved within this JRA is related to the characterization of PAPR distribution in NC-OFDM systems. It was observed that there is neither exact nor upper/lower bound of PAPR available in the literature for the NC-OFDM waveform. In that context, significant effort has been put to derive the closed-form formulas describing these bounds. The properties of the NC-OFDM transmission scheme in the context of PAPR analysis have been also developed. A paper reporting this achievement is now under preparation.

Detailed results have been presented in appendix section 4.8 and 4.9. The following activities have been identified for the future work:

- Strengthening the cooperation between Track 1 and Track 2 by direct implementation of the CC algorithms on hardware
- Further work on potential improvements of the cancellation carrier method in the context of non-contiguous transmission
- Investigation on the PAPR issues in the non-contiguous scheme.

2.6.4 Publications

[1] Pawel Kryszkiewicz, Hanna Bogucka "Advanced Interference Reduction in NC-OFDM Based Cognitive Radio with Cancellation Carriers" EUSIPCO 2014, September 2014, Lisbon, Portugal

[2] Paweł Kryszkiewicz, Hanna Bogucka “Nowa metoda redukcji interferencji w systemie radia kognitywnego z techniką nc-ofdm wykorzystująca informację kontekstową”, KKRRiT 2014, Warsaw, 11-13.06.2014 (in Polish)

2.7 JRA 1.3.3A on interference management techniques for heterogeneous networks

Leader: Jordi Pérez-Romero (UPC)

Researchers involved: Jordi Pérez-Romero, Katerina Koutlia, Ramon Agusti (UPC), Andreas Zalonis, Nikos Dimitriou, Andreas Polydoros (IASA), Adrian Kliks, Paweł Kryszkiewicz, Hanna Bogucka (PUT), Lila Boukhatem, Steven Martin, Tara Ali Yahia, Reben Kurda (UniPS)

2.7.1 Description of Activity

The main objective of this JRA is to propose solutions to the interference management problem in wireless Heterogeneous Networks (HetNets), ensuring an efficient use of the resources (power/frequencies) in order to achieve the desired QoS with minimum resource consumption, or alternatively, given a certain amount of resources, maximize the achievable capacity. The considered HetNets scenarios include OFDMA-based systems such as LTE-A with cells of different sizes, i.e. macrocells and small cells (picocells, femtocells, etc.) and the existence of Wi-Fi for traffic offloading.

Specific interference management techniques that are being under consideration in this JRA include: (i) power control techniques that consist in adjusting the transmitted power to reduce the interference generated to victim users, (ii) frequency domain techniques, in which orthogonal transmissions of different users are achieved by assigning different frequency resources to the users in the different cells that can potentially interfere, (iii) time domain techniques in which the users that suffer from interference are assigned resources in specific time periods where the interference is suppressed, (iv) traffic offloading techniques, in which part of the traffic generated by the cellular networks is offloaded through Wi-Fi networks (or other non-3GPP networks) thus reducing the interference in the cellular network.

The considered frequency domain techiques in this JRA include also the particular case of having some bands (e.g. Television White Spaces - TVWS) that can be used opportunistically depending on their availability to extend the capacity of the cellular networks. For that purpose the frequency assignment needs to take into account the spectrum availability at the TVWS band and perform a smart assignment ensuring that there is no harmful interference generated to primary users (i.e. TV receivers). In this respect, this JRA is closely related to JRA#G in WP2.1, entitled “Spectrum Occupation Measurements and Database Exploitation”, where a Radio Environmental Map (REM) is being built based on real measurements performed in different locations to be used as the input for the frequency assignment algorithms developed here.

Actually, the REM concept, as a database that dynamically stores different types of information about the environment plays a very relevant role in all the interference management techniques developed in this JRA. In this respect, as discussed later on in section 2.7.3, this JRA has been developing a REM-based architectural framework for supporting the developed techniques and it has identified the relevant contextual parameters to be stored in the REM for each technique.

2.7.2 Relevance with the identified fundamental open issues

This JRA covers the following fundamental open issues identified in deliverable D13.1:

- Efficient power adjustment techniques for reducing the interference between macro and small cells making use of context information stored in databases such as REMs, asessing the impact of accurate, inaccurate and/or outdated information on the system performance.

- Optimize the frequency domain intercell interference coordination for heterogeneous scenarios with both macrocells and small cells.

- Joint optimization of ABS and CRE parameters in heterogeneous networks.

- Allocation of shared spectrum (e.g. TVWS) in small cell scenarios. While the use of shared spectrum such as TVWS to extend the capacity in LTE and LTE-A networks has been found particularly relevant for small cell scenarios, there are actually still very few works that have addressed the problem of how to allocate TVWS spectrum in an optimized way.

2.7.3 Main Results Achieved in the Reporting Period and planned activities

The main results achieved during the reporting period November 2013 - October 2014 are summarised in the following:

A REM-based architectural framework has been proposed for supporting interference management techniques in HetNets including both LTE and Wi-Fi technologies. It consists of general layered architecture that considers the inclusion of global and local REM databases at different nodes of the network. Details can be found in Section 4.10.

The developed REM-based general framework has been particularized for three interference management techniques, including power control, optimization of the frequency dimension and data offloading towards the Wi-Fi network. Results have been obtained to assess the performance gains in terms of outage reduction, throughput increase or intercell interference reduction in different situations taking as a reference the baseline case without REM. Moreover, a first analysis of the impact of errors in the stored REM information in terms of the achieved performance has been carried out. Details can be found in Section 4.11.

A neighborhood cooperation algorithm for deciding the TVWS spectrum assignment to small cells has been proposed and evaluated. Details can be found in Section 4.12.

In conjunction with JRA#G in WP2.1, the computation of the maximum allowed transmit powers not to interferere with TV receivers when TVWS are allocated to small cells has been carried out based on real measurements performed in an indoor building. Details can be found in Section 4.13

An interference coordination scheme that exploits jointly the frequency, power and time dimensions has been proposed and assessed. Details can be found in Section 4.14.

The identified planned activities for the next year are listed in the following:

- Further definition and assessment of selected interference management techniques under the proposed REM-based framework, exploiting the frequency/time/power/dimensions, and analyzing the impact of errors in the stored REM information.
- Evaluation of TVWS assignment techniques for the deployment of small cells in indoor scenarios based on the measurements available from JRA#G in WP2.1.
- Development of the new schemes for efficient traffic offloading (via femtocells and WiFi access points) focusing on the reduction of the backhaul traffic in the core network of the mobile operator and on the overall system performance.

2.7.4 Publications

[1] J. Pérez-Romero, A. Zalonis, L. Boukhatem, A. Kliks, K. Koutlia, N. Dimitriou, R. Kurda, "On the use of Radio Environment Maps for Interference Management in Heterogeneous Networks", submitted to IEEE Communications Magazine, July, 2014.
[2] H. Bogucka, J. Pérez-Romero, "Small cells deployment in TV White Spaces with neighborhood cooperation", URSI General Assembly and Scientific Symposium, Beijing, China on August 16-23, 2014.
[3] N. Dimitriou, A. Zalonis, A. Polydoros, A. Kliks, O. D. Holland "Context-Aware Radio Resource Management in HetNets", WCNC 2014 (FutureHetNets workshop), April, 2014.

[4] Umbert, J.Pérez-Romero, F. Casadevall, A. Kliks, P. Kryszkiewicz, "On the use of Indoor Radio Environment Maps for HetNets Deployment", CROWNCOM conference, June, 2014,
[5] K. Koutlia, J. Pérez-Romero, R. Agustí, "Novel eICIC Scheme for HetNets Exploiting Jointly the Frequency, Power and Time Dimension", IEEE 25th Annual International Symposiumon Personal, Indoor and Mobile Radio Communications (PIMRC), Washington DC, USA, September, 2014.
[6] R. Kurda, L. Boukhatem, T. Ali Yahiya, M. Kaneko, "Power adjustment mechanism using context information for interference mitigation in two-tier heterogeneous networks", 19th IEEE Symposium on Computers and Communications (ISCC 2014), Madeira, Portugal, June 23-26 2014.

2.8 JRA 1.3.3B on game-theoretic energy-efficient control and resource allocation algorithms in heterogeneous networks

Leader: Luca Sanguinetti (CNIT-PISA)

Researchers involved: Luca Sanguinetti, Giacomo Bacci (CNIT-PISA), E. Veronica Belmega (CNRS-ENSEA), Ivan Stupia, Luc Vanderdorpe (UCL), Panayotis Mertikopoulos (CNRS), Merouane Debbah (CNRS-SUPELEC).

2.8.1 Description of Activity

The research activity within this JRA is focused on the development of game-theoretic energy-efficient resource allocation algorithms for HetNets and is mainly comprised of the following research directions. The first one focuses on subcarrier assignment and power allocation in HetNets with rate constraints and relies on non-cooperative game theory to study the properties of Debreu equilibria. The second one relies on the use of the quasi variational inequality (QVI) framework to study power allocation problem in HetNets in which different types of users may pursue different objectives. The third activity is focused on studying a non-cooperative game in which each player selfishly minimizes the power consumption while satisfying target SINR constraints. In contrast to the other two activities, this is done under the assumption that each transmitter has no knowledge about the propagation channel but can only exploit the ACK or NACK feedbacks generated at the link layer from the receiver. The fourth activity investigates the problem of energy-efficient power allocation (PA) in BICM-OFDM systems.

2.8.1.1 Energy-Aware Competitive Power Allocation for Heterogeneous Networks under QoS Constraints

Researchers involved: Luca Sanguinetti, Giacomo Bacci (CNIT-PISA), E. Veronica Belmega (CNRS-ENSEA), Panayotis Mertikopoulos (CNRS),

This research activity proposes a distributed power allocation scheme for maximizing energy efficiency in the uplink of OFDMA-based HetNets. The UE in the network are modeled as rational agents that engage in a non-cooperative game where each UE allocates its available transmit power over the set of assigned subcarriers so as to maximize its individual utility (defined as the user's throughput per Watt of transmit power) subject to minimum-rate constraints. The major objectives of this research activity are to study and analyze the equilibrium points and to develop distributed and iterative algorithms that let each player converge to the equilibrium without the need of any centralized unit.

2.8.1.2 Energy-Efficient Power Optimization in Heterogeneous Networks: A Quasi-Variational Inequality (QVI) Approach

Researchers involved: Luca Sanguinetti, Giacomo Bacci (CNIT-PISA), Ivan Stupia, Luc Vanderdorpe (UCL)

This research activity deals with the power allocation problem in a multipoint-to-multipoint network, which is heterogeneous in the sense that each transmit and receiver pair can arbitrarily choose whether to selfishly maximize its own rate or energy efficiency. This is achieved by modeling the transmit and receiver pairs as rational players that engage in a non-cooperative game in which the utility function changes according to each player's nature. To overcome the main limitations of existing methodologies, the underlying game is reformulated as a QVI problem and the powerful tools of the QVI theory are used: *i*) to study the uniqueness of the NE points; *ii*) and to derive novel algorithms that let players converge to the NE points in an iterative manner both with and without the need for a centralized processing.

2.8.1.3 Distributed power control over interference channels using ACK/NACK feedback

Researchers involved: Luca Sanguinetti (CNIT-PISA), Merouane Debbah (CNRS-SUPELEC)

This research activity focuses on a network composed of several single-antenna transmitter-receiver pairs in which each pair aims at selfishly minimizing the power required to achieve a given SINR. The transmitter-receiver pairs are modeled as rational agents that engage in a non-cooperative game. Most of the existing literature in this context relies on the assumption that the transmitter has perfect knowledge of the SINR measured at the receiver. This assumption does not hold true in practical applications and the only way for the transmitter to acquire this knowledge is through a return control channel. Although possible, however, this solution is not compliant with most of the current wireless communication standards in which the receiver only sends back an ACK whenever it is able to correctly decode the message and a NACK otherwise. The major objective of this activity is to derive a novel iterative and distributed algorithm that allows the transmitters to converge to the equilibrium point using only the limited feedback in the form of ACK or NACK over packet-oriented transmission links.

2.8.1.4 Distributed energy-efficient power optimization in BICM-OFDM systems

Researchers involved: Riccardo Andreotti (CNIT-Pisa), Filippo Giannetti (CNIT-Pisa), Paolo del Fiorentino (CNIT-Pisa), Vincenzo Lottici (CNIT-Pisa), Ivan Stupia (UCL).

The JRA investigates the problem of deriving an energy-efficient power allocation (PA) approach in small-cells (SCs) networks. In detail, the scenario consists of a given number of SCs, where, in each of them, a certain number of BIC-OFDM users transmit toward the associated small base station (SBS). All the users in a SC have their own quality-of-service (QoS), in terms of target goodput (GP) value, and transmit over orthogonal subbands according to the OFDMA-based access, avoiding intra-cell interference. However, all SCs exploit the same band, so that inter-cell interference arises causing a degradation of the signal-to-interference-plus-noise (SINR) of each user. Thus, relying on an energy-efficient design criterion, a distributed power allocation algorithm has been derived which minimizes the power allocated by every user in each SC guaranteeing their QoS and accounting for the inter-cell interference. The GP metric, which quantifies the trade-off between data rate and link reliability, entails a practical point of view, since it quantifies the actual performance of packet-oriented systems employing practical modulation and coding schemes. The analysis and algorithms proposed in this JRA are therefore of interest especially for Track 2 activities, which aim at assessing the real performance of a system, instead of exploiting theoretical-oriented metrics such as the link capacity.

The activity takes into account the objectives and open issues identified at the beginning of project and listed in both the description of work (DoW) and year 1 deliverable of WP1.3.3. In fact, the JRA investigated and proposed a solution for the derivation of (distributed) resource allocation (RA) techniques to minimize energy consumption in BICM-OFDM small-cell networks, supporting demanding and/or content-rich applications. Moreover, game theory was adopted to describe the distributed RA problem, in that it offers a suitable and effective tool to analyze the issues related to the existence and uniqueness of the solution.

2.8.2 Relevance with the identified fundamental open issues

As identified in Section 2.3.2 of D13.1, most of the state-of-the-art game-theoretical solutions are focused on maximizing the spectral efficiency of wireless communication systems while only few schemes aim at addressing the energy efficiency maximization problem. To fulfil this lack, the following open issues have been identified in D13.1:

- The need for the definition of new metrics taking into account the power expenditure and the need to formulate the problem under investigation as non-cooperative or cooperative games with complete or incomplete knowledge of some the system parameters.
- The need for studying and analyzing the existence, uniqueness, efficiency and stability of the equilibrium points of the resulting games.
- The need for the development of energy-efficient distributed algorithms able to approach the performance of the centralized solutions under different operating conditions and scenarios.

All the research activities carried out within this JRA attempt to solve the above open issues in the considered scenarios.

2.8.3 Main Results Achieved in the Reporting Period and planned activities

The main results achieved by the different research activities within this JRA in the reporting period are summarized as follows.

2.8.3.1 Energy-Aware Competitive Power Allocation for Heterogeneous Networks under QoS Constraints

The major findings of this research activity are the analysis and design of energy- efficient power allocation policies in a HetNet setting where small-cell networks coexist with macro-tier cellular systems based on OFDMA technology. In particular, focusing on the uplink case, we propose a game-theoretic framework where each UE adjusts the allocation of its transmit power (over the available subcarriers) so as to maximize unilaterally its individual link utility subject to a minimum rate requirement that must be satisfied. Specifically, each user's energy-aware utility function is defined as the achieved throughput per unit power, accounting for both the power required for data transmission and that required by the circuit components of each UE (such as amplifiers, mixer, oscillator, and filters). The relevant solution concept is that of Debreu equilibrium, a generalization of NE, which accounts for the case where an agent's set of possible actions depends on the actions of its opponents. Since the problem at hand might not be feasible, Debreu equilibria do not always exist. However, using techniques from fractional programming, we provide a characterization of equilibrium power allocation profiles when they do exist. In particular, Debreu equilibria are found to be the fixed points of a water-filling best response operator whose water level is a function of minimum rate constraints and circuit power. Moreover, we also describe a set of sufficient conditions for the existence and uniqueness of Debreu equilibria exploiting the contraction properties of the best response operator. This analysis provides the necessary tools to derive a power allocation scheme that steers the network to equilibrium in an iterative and distributed manner without the need for any centralized processing. Numerical simulations are then used to validate the analysis and assess the performance of the proposed algorithm as a function of the system parameters, also discussing key design tradeoffs to meet 5G requirements (e.g., obtaining more than 500 b/s/Hz/km^2 area spectral efficiency) with a reasonable amount of physical resources (e.g., bandwidth and transmit power), and of complexity at the receiving stations, such as minimal information requirements at the user level and number of antennas.

Challenging open issues for further work include: *i*) assessing the feasibility of the problem given a particular network realization for the multicarrier case; *ii*) assessing (and possibly reducing) the algorithm's complexity as a function of the system parameters; and *iii*) evaluating the impact of different receiver architectures (such as multiuser, zero-forcing, and interference cancellation techniques) on the spectral and energy efficiency of the network.

2.8.3.2 Energy-Efficient Power Optimization in Heterogeneous Networks: A Quasi-Variational Inequality Approach

The underlying game is reformulated as a QVI problem using convex fractional program theory. Unlike the traditional VI framework, that has been widely applied in the wireless communications field, the use of QVI theory for developing numerical algorithms is relatively recent and is shown to be very helpful in overcoming the main limitations of existing approaches, which fail to provide closed-form conditions on the uniqueness of the equilibrium points and on the convergence properties of iterative solutions. Towards this goal, a two-step approach is used. First, the energy efficient maximization problem introduced is reformulated as a QVI using convex fractional programming theory. The same approach is then exploited to reformulate the heterogeneous game as a QVI. This is *per-se* sufficient to elaborate some insights on the properties of the NE points and to provide us with all the mathematical tools to study the uniqueness of the NE points of the heterogeneous game, and the convergence properties of iterative algorithms. In particular, we first propose a *centralized* approach, which relies on an iterative method for solving QVIs whose convergence is guaranteed under mild assumptions. Then, we propose an alternative solution exploiting the equivalence between the QVI and a nonlinear complementary problem, which gives each pair the possibility to reach the NE in a *distributed* manner without the need for any centralized processing. The developed solutions are then validated by means of extensive simulations.

This work must be considered as a first attempt in using the QVI theory for dealing with energy efficiency in a competitive environment. We do believe that the developed framework will be of great help to deal with several interesting extensions (as the VI theory was useful to better study the rate maximization problem). For example, the above results might be in principle extended to the design of energy-efficient solutions in which additional constraints can be incorporated. This might be the case of minimum data rate requirement or maximum allowed interference levels. All this is left for future work.

2.8.3.3 Distributed power control over interference channels using ACK/NACK feedback

The major goal of this activity is the development of a distributed algorithm to selfishly minimizing the power consumption while satisfying target SINR constraints in interference channels characterized by single- antenna transmitter-receiver pairs operating over the same frequency band or time slot. In particular, we have first modeled the problem as a non-cooperative game with perfect channel state information and then we have solved it assuming that each transmitter has no knowledge about the propagation channel but could only exploit the ACK or NACK feedbacks generated at the link layer from the receiver. This choice has been motivated by the fact that it is compliant with many wireless communication standards and avoids the need of introducing a suitably designed return control channel. Accordingly, we have proposed an iterative and distributed algorithm inspired by best response dynamics in which (at each step) every transmitter updates its power exploiting a local estimate of its current SINR at the receiver. The latter is learned step-by-step via an updating rule based on the 1-bit feedback information given by ACK or NACK. The performance of the proposed solution has been evaluated by means of numerical results in the uplink of a small cell network. It turns out that the algorithm converges reasonably fast to the generalized NE point of the underlying game with perfect channel state information.

Further research is needed to provide an analytical proof about the convergence of the iterative procedure.

2.8.3.4 Distributed energy-efficient power optimization in BICM-OFDM systems

The main achieved results can be summarized as follows. First, the PA problem subject to GP constraint was analyzed and solved in point-to-point communication links. Then, the problem was extended to a distributed PA problem subject to per-user GP constraints in SC networks and solved. This problem was described as a noncooperative game and the existence and uniqueness of its solution, corresponding to the generalized Nash equilibrium (GNE) of the game, were analytically derived. The convergence of the distributed PA algorithm, based on the best-response strategy, was also analytically assessed. The next steps consist in studying a price strategy that allows to improve the efficiency of the GNE and studying how the game changes if the feasible modulation orders and coding rates are included in the strategy set.

2.8.4 Publications

2.8.4.1 Energy-Aware Competitive Power Allocation for Heterogeneous Networks under QoS Constraints

[1] G. Bacci, V. Belmega, L. Sanguinetti 'Distributed energy-efficient power optimization in cellular relay networks with minimum rate constraints', *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Florence, Italy, May 2014.
[2] G. Bacci, V. Belmega, L. Sanguinetti 'Distributed Energy-Efficient Power and Subcarrier Allocation for OFDMA-Based Small Cells', *IEEE International Conference on Communications (ICC)*, Sydney, Australia, June 2014.
[3] G. Bacci, V. Belmega, P. Mertikopoulos, L. Sanguinetti 'Energy-Aware Competitive Link Adaptation in Small-Cell Networks', *International Workshop on Resource Allocation in Wireless Networks (WiOpt - RAWNET)*, Hammamet, Tunisia, May 2014. (INVITED PAPER)
[4] G. Bacci, E. V. Belmega, P. Mertikopoulos, and L. Sanguinetti 'Energy-Aware Competitive Power Allocation in Heterogeneous Networks with QoS constraints', submitted to *IEEE J. Select. Areas Commun.* (Special Issue on HetNets), July 2014.

2.8.4.2 Energy-Efficient Power Optimization in Heterogeneous Networks: A Quasi-Variational Inequality Approach

[1] Stupia, L. Sanguinetti, G. Bacci, L. Vanderdorpe 'Distributed Energy-Efficient Power Optimization for Relay-Aided Heterogeneous Networks', *International Workshop on Wireless Networks (WiOpt - WCN)*, Hammamet, Tunisia, May 2014. (INVITED PAPER)
[2] Stupia, L. Sanguinetti, G. Bacci, L. Vandendorpe 'Energy-Efficient Power Optimization in Heterogeneous Networks: A Quasi-Variational Inequality Approach', submitted to *IEEE Trans. Signal Process.*, revised June 2014.

2.8.4.3 Distributed power control over interference channels using ACK/NACK feedback

[1] R. Andreotti, L. Marchetti, L. Sanguinetti, M. Debbah 'Distributed power control over interference channels using ACK/NACK feedback', *IEEE Global Communications Conference (GLOBECOM)*, Austin, Texas, Dec. 2014.

2.8.4.4 Distributed energy-efficient power optimization in BICM-OFDM systems

[1] Del Fiorentino P., Andreotti R., Lottici V., Giannetti F., Stupia I., "Distributed Power Allocation for Cognitive Noncooperative BIC-OFDM Systems", in Proc. of Eleventh

International Symposium on Wireless Communication Systems (ISWCS), 2014, Barcelona, Spain.

[2] Del Fiorentino P., Andreotti R., Lottici V., Giannetti F., Stupia I., Vandendorpe L., "Distributed Power Allocation Based On PER Minimization for Noncooperative Multicarrier Systems Under Interference Constraints", in Proc. of European Conference on Networks and Communications (EuCNC), 2014, Bologna, Italy.

[3] Andreotti R., Lottici V., Giannetti F., Stupia I., Vandendorpe L., "A Game Theoretical Approach for Reliable Packet Transmission in Noncooperative BIC-OFDM Systems", in Proc. of IEEE ICC 2013, Budapest, Hungary, 2013.

2.9 JRA 1.3.3C on self-configuration and optimization of a hybrid LTE Femto - M2M network for smart city applications

Leader: Danilo Abrignani (CNIT-UniBO)

Researchers involved: Danilo Abrignani, Roberto Verdone (CNIT-UniBo), Lorenza Giupponi (CTTC)

2.9.1 Description of Activity

In this JRA we tackle the uplink scheduling problem in an urban scenario for future smart cities. We foresee Machine-to-Machine (M2M) traffic generated by a Mobile Wireless Sensor Network (MWSN), which is characterized by multiple peculiarities: (i) M2M traffic generated by most services/applications is bi-directional, which means that the network must provide the mechanisms to identify a device and know its status; (ii) different applications have different requirements in terms of throughput, maximum tolerable packet loss rate, maximum delay, etc. as it is influenced by the information lifetime. We consider that the aggregated M2M traffic is collected and scheduled to a gateway connecting to the core network, by LTE small cells intensively deployed over the street lamps of the city. The small cells could be deployed by the network operator, or by the provider of smart city solutions.

The M2M traffic, has to coexist with Human to Human (H2H) traffic, so that the small cells have to take care of handling this coexistence and properly scheduling both traffic types, in a set of resources which is limited by the intercell interference issues arising in this intensively deployed scenario. M2M traffic is different with respect to human generated traffic, in that generally the amount of data that is necessary to transmit is very low, and cellular networks are not designed to transmit this information efficiently. As a result, we face a scheduling problem where, on the one hand we need to take into account intercell interference coordination issues, and on the other hand we have to serve a huge amount of users with very different requirements in terms of delay, latency, throughput, etc.

For the time being we are focusing our efforts on the uplink segment of the network, as it seems the most challenging issue, due to the fact that cellular networks are especially designed for supporting high traffic mostly in the downlink. In addition, also from the point of view of intercell interference coordination in small cell scenarios, the state of the art is intensively populated by contributions related to the downlink problem, while the uplink problem is more unexplored. However, as new M2M applications arise, we will also extend our approach to the downlink segment and to the relations and decoupling of the two links. The SC-FDMA (Single Carrier Frequency Division Multiple Access) scheme standardized for the LTE (Long Term Evolution) uplink, poses also several challenges for the scheduling design, related with the constraint of contiguity of Resource Block (RB) allocation.

Some interesting inputs for our work come from the JRA6 of WP2.2. JRA6 deals with the Internet of Things scenario and it aims to evaluate different paradigms and standards for M2M application in wireless sensor networks. More in details, JRA6 can provide input on real behaviour of different protocols in terms of Packet Error Rate (PER) and signalling overhead; which has to be transmitted over the LTE network and towards the M2M server. Also this signalling traffic, which in JRA6 is estimated to increase the data traffic by a 60-80%, should be properly scheduled over the LTE network. Hence, our M2M traffic model can be adapted based on this information.

2.9.2 Relevance with the identified fundamental open issues

The work that is being carried out is relevant to the fundamental open issues that have been identified in section 3.9 of Deliverable D13.1, as it aims to propose a solution for the uplink scheduling of M2M traffic, which is one of the main open problems when it comes to schedule M2M traffic in a LTE network. In particular, with M2M traffic coming into play the scheduling entities have to deal with extremely diverse QoS criteria. For example, delay tolerance may span from tens of ms (vehicle collision) to several minutes (environmental monitoring), and the error rate tolerance, scale similarly. In addition, the LTE network is generally designed for asymmetric traffic distribution between uplink and downlink, with predominance in the downlink segment, while M2M traffic has a significant impact on the uplink. This is why the problem of scheduling M2M traffic in the uplink segment is particularly challenging.

2.9.3 Main Results Achieved in the Reporting Period and planned activities

During the reporting period, we have obtained the following achievements (details can be found in Annex, section 4.19):

Achievement 1 - Scheduling opportunities: We have evaluated the scheduling opportunity of traffic in a densely deployed small cell networks, based on the 3GPP uplink constraint of contiguous RB allocations. The results have been presented in IC1004 Cost Meeting in Ferrara in February 2014, and in EuCNC 2014.

Achievement 2 – Implementation: We have defined a Mixed Integer Linear Programming (MILP) model for the LTE Uplink radio resource assignment problem. Currently, we are testing this model, through a MILP solver (IBM ILOG Cplex) and implementing the model in the ns3 LENA simulator. We expect to obtain stable results by September 2014 and so we plan a submission in one of the upcoming conferences.

2.9.4 Publications

[1] M.D. Abrignani, L. Giupponi and R. Verdone, Evaluation of M2M Scheduling Opportunities in a LTE Small Cell Network for Smart City Applications, - Cost Meeting - IC1004 TD(14)09040 –Ferrara, Italy 5-7 February, 2014

[2] M.D. Abrignani, L. Giupponi, A. Lodi and R. Verdone, Mixed-Integer Linear Programming approaches for the LTE Uplink Radio Resource Assignment model, Special Session Advanced Techniques for Energy and bandwidth efficient communications - EuCNC 2014 – Bologna, Italy 23-26 June 2014 (Presentation)

2.10 JRA 1.3.3D on Radio resource allocation algorithms in cognitive radio networks with outdated CSI

Leader: Filippo Giannetti (CNIT-Pisa)

Researchers involved: Riccardo Andreotti (CNIT-Pisa), Paolo Del Fiorentino (CNIT-Pisa), Filippo Giannetti (CNIT-Pisa), Vincenzo Lottici (CNIT-Pisa), Marc Moeneclaey and Jeroen Van Hecke (UGent, Associate Partner Type II).

2.10.1 Description of Activity

This JRA investigates novel resource allocation (RA) techniques for bit-interleaved coded OFDM (BIC-OFDM) transmission systems where the transmission parameters are adapted according to the channel state information (CSI) in order to provide reliable and efficient data packet delivery over time-varying frequency selective channels. Differently from the majority of RA problems considered in the literature, this JRA focuses on the goodput (GP) as the figure of merit, defined as the number of information bits delivered in error-free packets per unit of time.

More specifically, the reference scenario is a cognitive radio (CR) system made of an unlicensed (secondary) transmitter-receiver pair, together with several unlicensed decode-and-forward (DF) relay nodes (RNs), all of them operating in BIC-OFDM mode in the same band as a licensed user (primary user, PU), plus other PUs that operate in the adjacent bands.

The research activity aims first at devising novel RA methods for choosing the best relay in a dual-hop scheme, and for selecting the best modulation, code rate and transmission power settings for each OFDM subcarrier to be used by the transmitter and by the selected relay. The aim is to maximize the GP metric for both the "transmitter-relay" and for the "relay-receiver" links, in the presence of constraints on the amount of interference caused to PUs. Towards this goal, a link performance prediction (LPP) methodology is employed to provide an estimate of the GP, referred to as "expected GP" (EGP), which represents the objective function to be maximized by the RA problem. Furthermore, in order to get an accurate performance prediction also over time-varying channels, the effective signal-to-noise ratio (SNR) mapping (ESM) technique, named κ ESM (originally proposed in ref. [15] of Sect. 4.20.4), was extended to the more realistic case wherein only imperfect/outdated channel state information (CSI) is available. Subsequently, the proposed LPP method is exploited as the core of a novel RA strategy in a multi-hop transmission system, still operating in a CR environment. Accordingly, a new EGP function shall be properly defined for a multi-hop scenario, which shall evaluate the overall GP performance relevant to the whole link from the transmitter to the receiver, and this will be used for defining a selection technique for the "best-path" across the available active RNs. More details are reported in Sect. 4.20 of the Annex.

2.10.2 Relevance with the identified fundamental open issues

The research work (which started in Summer 2013, after the admission of UGent as associate partner of the NEWCOM# consortium) is relevant to the fundamental open issues that have been identified in the survey on the state of the art, reported in Sect. 4.20.1 of the Annex. More specifically, the research activity aims at providing new RA techniques for "real-world" packet-oriented multicarrier systems. As matter of fact, the vast majority of the literature develops RA strategies based upon theoretically-oriented performance metric, such as the capacity or the mutual information, which are of little use in the practice. Instead, this JRA uses the GP metric, which is defined as the number of information bits delivered in error-free packets per unit of time, and thus it allows to characterize in a more suitable way the actual performance of packet-oriented communication systems. Furthermore, typical impairments such as inaccurate/outdated estimates of channel parameters are taken into account, too. The GP provides a meaningful "layer-3" performance figure which enables a truly cross-layer and a more realistic design of next generation wireless mobile communication systems.

2.10.3 Main Results Achieved in the Reporting Period and planned activities

During the reporting period, a new RA technique for CR BIC-OFDM systems with the presence of a secondary transmitter-receiver pair and several PUs was devised. The customary LPP κ ESM scheme was enhanced and was made capable to evaluate the EGP at the transmitter in a more accurate way, thus enabling a more robust and competitive RA strategy. Moreover, real-world impairments, such as imperfect channel estimate and outdateness of the estimates due to the time-varying nature of the channel, have been taken into account. Preliminary numerical results validate the effectiveness of the new LPP model and of the relevant RA strategy. Actually, the proposed approach revealed robust, even for low values of the channel correlation coefficient, and was shown to outperform the old RA strategy based upon the conventional implementaion of the κ ESM method.

2.10.4 Publications

[1] Del Fiorentino, P.; Van Hecke, J.; Andreotti, R.; Lottici, V.; Moeneclaey, M.; Giannetti, F. “Link Resource Adaptation for BIC-OFDM Systems with Outdated Channel State Information,” *European Wireless, 2014*, 14-16 May 2014.

[2] Van Hecke, J.; Del Fiorentino, P.; Lottici, V.; Moeneclaey, M.; Giannetti, F.; “Resource Allocation for Multicarrier Cooperative Cognitive Radio Networks with Imperfect Channel State Information,” *PIMRC, 2014*, 2-5 September 2014.

3. General Conclusions and Prospects

In the present WP the focus is on specific research areas and research problems regarding *resource efficiency* (resource being energy or bandwidth) and in which the partners have already demonstrated experience and knowledge, thus allowing them to effectively collaborate and further promote their common research activities. The first deliverable provided an analysis of the State of the Art and identified the underlying fundamental research issues in the thematic areas of interest. In this second deliverable, each JRA presents the description of the activity along with an illustration of the adherence to and relevance with the identified fundamental open issues, a presentation of the main results, and a roadmap for the future joint research.

Although the research work in this WP, as part of Track 1 of the Newcom# project, centers on theoretical algorithmic development, in most activities practical issues have been taken into consideration by appropriate modelling of the uncertainties encountered in the real world. In various JRAs a connection to Track 2 activities has already been performed and in some others it is currently under investigation.

In Task 1.3.1, significant achievements have been obtained by the Newcom# researchers. First, in the area of communication with energy harvesting nodes, where several scenarios have been addressed and techniques have been proposed. An important aspect of this work was the initiation of a connection to a Track 2 JRA in which the researchers worked jointly on the energy modelling and profiling of the physical layer of a modern wireless communication system and developed a hardware implementation of an interference mitigation technique for LTE systems. The outcomes of this activity are reported in a series of publications (details in section 2.1). Second, an activity on the signal detection solutions has been initiated and will continue in the next year. The promising results on outlier detection for wireless sensor networks will be tested in the context of the DATASENS platform. Third, promising results on the novel concept of JPCD have already been obtained in the context of any Wi-Fi network. The related objective in the third year will be to extend these results to LTE, LTE-A, and address new issues pertaining to these communication architectures. Some of the obtained results are to be translated to the OpenAirInterface platform of WP 2.3: Flexible communication terminals and networks. Finally, the first results obtained during this second year on energy efficient probing in CSMA based multi-rate ad hoc networks are ready for publication. The work in the third year will also focus on energy efficiency of underwater acoustic networks.

The key achievements obtained during the second project year within Task 1.3.2 are also very promising. First, it can be stated that a further step has been taken toward practical realization of the FMBC based systems for future wireless applications. The findings presented by the Newcom# researchers at major conferences and in journals allow the conclusion that the FBMC-oriented transmission scheme can be viewed as one of the key candidates for future advanced communication systems. Second, the observed average rate in the scenario when BANs are utilized as ad-hoc MIMO system supporting regular transmission proved the validity of this important concept. It opens new research directions for the practical application of smart clothes in everyday life. Third, due to the direct relation with Track 2, the algorithms developed for out-of-band emission reduction in the non-contiguous schemes, as well as PAPR analysis have been partially verified in hardware implementations, thus proving the validity of the concept of primary and secondary system coexistence when the former utilizes a very narrow frequency band. Further work in this area is expected in the final year of the project.

In Task 1.3.3 there was significant progress on algorithmic developments by using analytical tools of game theory as well as other mathematical theories specifically tailored to the development, study and analysis of distributed algorithms. In addition, mechanisms and schemes that introduce incentives for opportunistically exploiting the unused access capacity of different network tiers were also investigated. In the related activity that proposes allocation strategies of shared spectrum (TVWS) in small cell scenarios, it is shown that the frequency assignment needs to take into account the spectrum availability at the TVWS band and perform a smart assignment which ensures there is no harmful interference generated to primary users. In this respect, in conjunction with JRA#G of WP2.1, a computation of the maximum allowed transmit power so as not to interfere with TV receivers when TVWS are allocated to small cells has been carried out, based on real measurements performed in an indoor building. Further cooperation with this Track 2 activity is expected in the third year. Similarly, a connection to a Track 2 activity has been established in the JRA dealing with hybrid LTE Femto - M2M networks. More specifically, within Track 2 the real behaviour of different protocols in terms of Packet Error Rate (PER) and signalling overhead – which has to be transmitted over the LTE network and towards the M2M server – has been evaluated, and this input will help in the adaptation of the M2M model used in this activity.

As it is shown in this deliverable, all JRAs have produced results that were presented or submitted in scientific journals, conferences and workshops. It is expected that the results and the dissemination activities will further accelerate in the last year of the project. Furthermore, in the last year, an important parameter in all the various efforts will be in the enhancement of Track 1/Track 2 collaborations that will eventually lead to contributions to the EuWIn repository.

4.Annex I: Detailed Description of Main technical WP Achievements

This Annex contains a detailed description of the aforementioned achievements of each JRA.

4.1 Achievements JRA 1.3.1A – Resource allocation and scheduling strategies for energy harvesting devices

In this section, we will present some of the most interesting techniques and results obtained in the framework of the JRA 1.3.1A during the last year. From all the techniques that we have investigated, the three most representatives will be presented in the sequel. First, we will address the scenario of simultaneous information and power transfer in multiuser MIMO networks. The second problem that will be analysed presents strategies for dynamic on/off switching of transmitters for sustainable networks. The last technique to be studied concerns the user association for load balancing in heterogeneous networks with energy harvesting transmitters.

4.1.1 Simultaneous information and power transfer in multiuser MIMO networks

Energy harvesting is a promising technology to provide longer connectivity to battery-powered nodes in wireless networks [1], [2]. Such technology enables to recharge the batteries of the network terminals and, thus, to enhance their lifetimes. Traditionally, energy harvesting techniques have been developed based on energy sources such as for example wind or solar energy. Nevertheless, there are other techniques that could be applied to moving sensors (this may be the case of cellular phones) based on piezoelectric technologies. Additionally, ambient radio frequency (RF) signals can be used as a source for energy scavenging. Unfortunately, some measurements in today's urban landscape show that the actual strength of the received electric field is not high and, thus, the proximity to the transmitter is important [1].

In this sense, it is important to emphasize that the newer applications require higher data rates and that this implies that more capacity efficient network deployments must be considered. Up to now, this increase in capacity efficiency has been shown to be achieved through the deployment of short-distance networks1 (e.g. femtocells [3]). The use of shorter distances in this kind of networks allows increasing the received power levels and, consequently, to make mobile terminals to be able to harvest power from the received radio signals when they are not detecting information data. This is commonly named as wireless power transfer.

The concept of simultaneous energy and data transmission was first proposed by Varshney [4]. He showed that, for the single-antenna additive white Gaussian noise (AWGN) channel, there exists a nontrivial trade-off in maximizing the data rate versus the power transmission. Later, in [5], authors extended the previous work considering frequency selective single-antenna AWGN channels. In [6] (and its journal version [7]), authors consider a multiple-input multiple-output (MIMO) scenario with one transmitter capable of transmitting information and power simultaneously to two receivers. They proposed two receiver architectures, namely time-switching and power-splitting that was able to combine both sources (information and energy) at the same time. There is another extension that considers the case of wireless information and power transfer with imperfect channel state information (CSI) [8]. In that work, authors proposed a robust beamforming design policy in the same scenario as in [6], but considering imperfections in the channel knowledge.

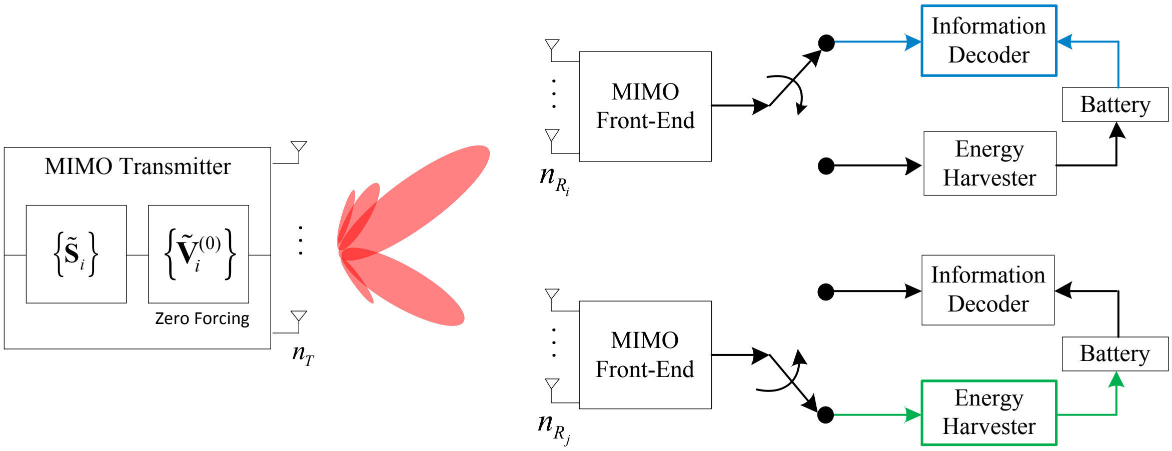

Figure 4-1: General scenario of simulataneous information and power transfer in multiuser MIMO networks.

The scope of this research is to extend the work in [6] and [8] by considering that multiple power harvesting nodes and information receivers are present in the system. We model the receivers as battery-limited nodes and, thus, they need to recharge the batteries to prolong the network lifetime. This energy scavenging is performed through dedicated power transmission from the transmitter to the individual receivers. We assume that there are two predefined groups of users to be served, one for power reception to recharge the batteries and another for information reception. The idea is that the power harvesting users benefit from the radiated power intended to the information receivers. In this context, we consider the sum-rate among the information receivers as the utility function to be optimized considering individual power harvesting constraints, see **Figure 4-1**.

The overall resource allocation strategy is modelled as a convex optimization problem where the objective is given by the sum-rate of the information users and individual harvesting constraints are taken into account explicitly. If we consider a multiuser MIMO network with linear precoding optimization, the optimization problem looks like:

$$
\begin{aligned}
&\underset{\{\mathbf{S}_i\}_{\forall i\in\mathcal{U}_I}}{\text{maximize}} && \sum_{i\in\mathcal{U}_I} \log\det\left(\mathbf{I} + \mathbf{H}_i\mathbf{S}_i\mathbf{H}_i^H\right) \\
&\text{subject to} && C1: \sum_{j\in\mathcal{U}_E} \mathrm{Tr}\left(\mathbf{H}_j\mathbf{S}_i\mathbf{H}_j^H\right) \geq Q_j, \quad \forall j\in\mathcal{U}_E \\
& && C2: \sum_{i\in\mathcal{U}_I} \mathrm{Tr}\left(\mathbf{S}_i\right) \leq P_T \\
& && C3: \mathbf{H}_k\mathbf{S}_i\mathbf{H}_k^H = 0, \quad \forall k\neq i, \ k,i\in\mathcal{U}_I \\
& && C4: \mathbf{S}_i \succeq 0, \quad \forall i\in\mathcal{U}_I
\end{aligned}
\tag{4.1.1}
$$

The overall problem can be easily checked to be convex. The particular structure of the optimum covariance matrix can be found in [9] as well as the details of the modelling and a detailed explanation of the feasibility of the problem. Additionally, in the paper, we have characterized the existing trade-off between the sum-rate the information users achieve and the energy that the other users harvest (known as rate-energy region). The proposed algorithm is based on the primal-dual decomposition approach where an iterative procedure that iterates among the primal variables and the dual variables is performed.

For a particular example of simulation parameters set up, the multidimensional rate-energy curve is depicted in **Figure 4-2**, where, for the sake of simplicity, only two harvesting users and two information users are considered.

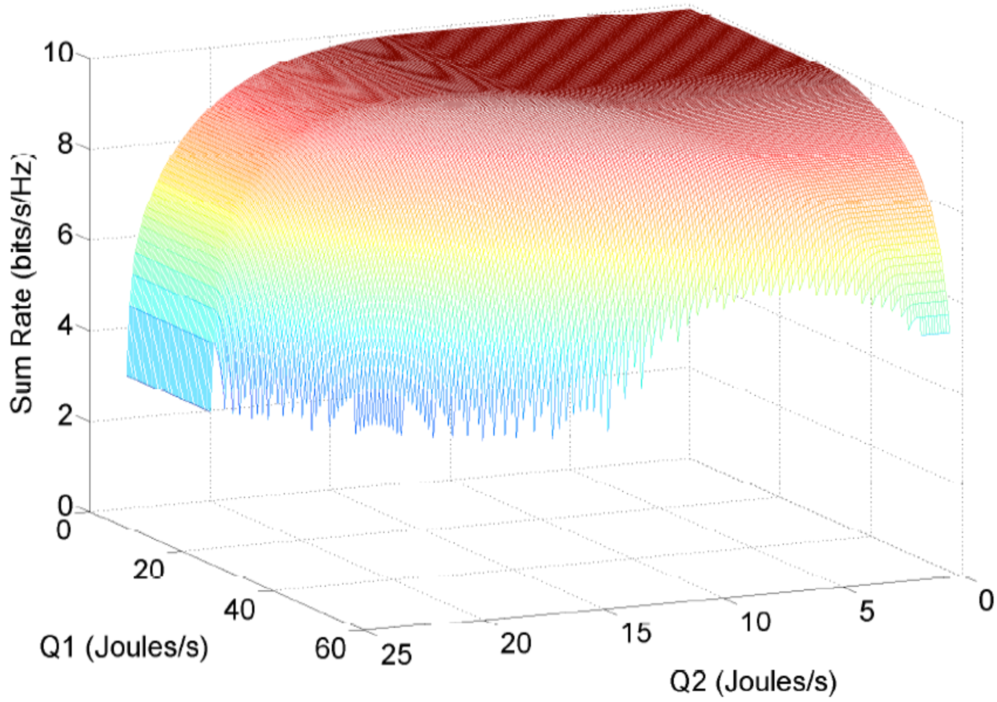

Figure 4-2: Representation of the three-dimensional trade-off Rate-Energy region.

As a matter of future work, we are designing scheduling strategies to decide which users must go into each of the two subsets, i.e., information users or harvesting users, in order to maximize the network throughput and the lifetime of the network nodes.

4.1.2 Dynamic on/off switching strategies of transmitters for sustainable networks

In this section, we propose strategies for switching on/off transmitters (or base stations (BS)) placed at the same location (sharing the same telecommunications tower) with fully overlapped coverage areas and using different frequencies. For simplicity in the development, we consider that just two BSs are placed at such site, but the results can be extended to any number of BSs. These transmitters are to be powered solely with solar panels and batteries. In real deployments, the energy units (batteries and solar panels) are dimensioned assuming that transmitters are always active transmitting at full power, without taking into account directly the current traffic demand.

With the objective of reducing the investment on energy units, we develop a procedure for switching on and off BS that does not degrade the quality of service experience by the users and additionally, the procedure also minimises the BS power consumption. We would like to remark that switching off a particular BS affects the network topology because the traffic that was originally served by the BS to be switched off has to be either transferred to nearby BSs or dropped. The obtained energy savings are directly translated into a more efficient energetic dimensioning (i.e., reduction of the sizes of the batteries and solar cells) and, thus, a reduction of the capital expenditures (CAPEX).

In the literature, there are some works dealing with the problem of switching on/off BSs. For example, in [10], a strategy is developed to decrease the energy consumption by switching off BSs when the activity is low under the constraint of keeping the coverage unaltered. The strategies are developed within the framework of stochastic geometry and, therefore, are well suited for the case of having many BSs at random positions, which does not fit the rural scenarios considered in this work. In [11], a strategy is presented taking into account that the traffic profile is time varying and under the objective of minimizing the energy consumption of the network assuming that there are many BSs uniformly distributed within the area of interest. [12] defines different possible states for the BSs (active mode, sleep mode, etc) in order to develop a switching strategy between the states depending on the instantaneous traffic load. This is achieved by expanding the coverage areas of the BSs that remain active. In [13], [14], the authors propose a sleeping algorithm for the BSs assuming that the distances between the users and their associated BSs are known. A more complex problem is analysed in [15], where a scenario with several BSs from different operators are considered. That paper introduces the cost that has to be paid by an operator when its subscribers have to be served by another operator due to the fact that some BSs have been switched off.

It is important to remark that in the previous works in the literature, the decision to switch off BSs was based only on the traffic demand, while the present work the decision to switch off BSs is taken under the criterion of minimizing the overall energy consumption.

We consider perfect and imperfect knowledge of the hourly traffic profile for defining the switch on/off procedure. In the latter case, a robust Bayesian strategy philosophy is adopted for tackling the error modelling in the traffic profile information. In order to determine whether a BS should be switched off or not, we need to measure and compare the required power that is needed for both configurations, i.e., a single BS or two BSs, to serve the users with a specific traffic demand as the configuration of single BS is only admissible if with one BS we can provide the service required by the users with a blocking probability lower than a pre-established threshold related with the QoS. In Table 4-1, we present the procedure developed to obtain the switching threshold when we have a single type of traffic and the traffic profile is perfectly known.

1:	Compute the mean power required by the two configurations (one and two HNBs) for all possible traffic rates (λ_0), $P_{1\mathrm{HNB}}(\lambda_0)$ and $P_{2\mathrm{HNB}}(\lambda_0)$.
2:	Let λ be the maximum traffic that can be supported with one HNB fulfilling the maximum blocking probability constraint. If $P_{1\mathrm{HNB}}(\lambda) < P_{2\mathrm{HNB}}(\lambda)$, then $\lambda_{TH} = \lambda$. Otherwise, λ_{TH} is the value of λ for which $P_{1\mathrm{HNB}}(\lambda) = P_{2\mathrm{HNB}}(\lambda)$.
3:	Switch off one of the two HNBs in all time instants m where $\lambda_{TH} \geq \lambda_0$.

Table 4-1 Threshold computation for switching on/off BSs with known traffic profile.

For the case of imperfect traffic knowledge, we consider a robust design where we first estimate the traffic profile and then we derive the new threshold for switching on/off the BS based on the outage probability criterion. We basically want to minimize the events that will make us decide to shut down one of the BSs when actually both should be on. The concrete mathematical formulation of the robust threshold can be found in [16].

Concerning the simulations results, let us denote that the simulation parameters are taken from a real deployment that is being studied and sized at the moment in the framework of a European project (TUCAN3G, http://www.ict-tucan3g.eu). The specific details of the simulation parameters can be found in the deliverables of such project which are fully accessible.

Figure 4-3 shows the daily traffic profile during for a specific location with the threshold λ_{TH} calculated for different types of BSs, but the two BSs are the same. As it can be observed from the figure, if HNB3 is selected, the configuration with 2 BSs is only needed in 4 hours per day (16% of the time). The remaining hours, with only one BS active would be sufficient.

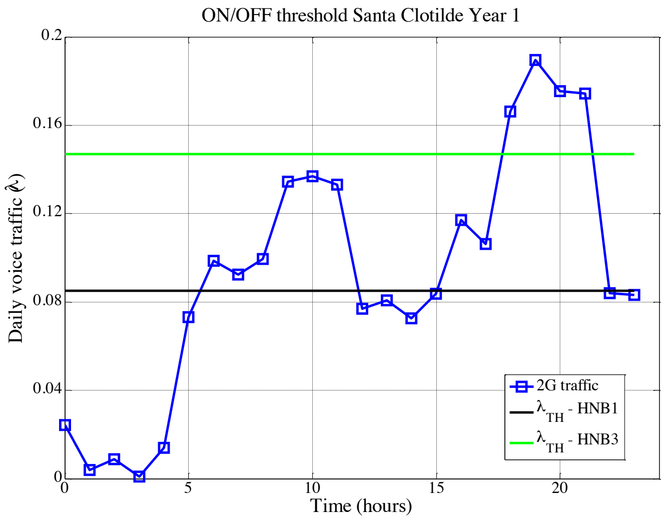

Figure 4-3: Daily traffic evolution with threshold depicted.

Once we know the λ_{TH}, we are able to set an on-off policy strategy where only two BSs are on when necessary. Given that, we are able to compute the amount of average energy consumed by the BSs throughout the day (considering that if a BS is off, it still consumes some power according to the model in [17]). With this consumption model, we can re-size the solar panels as well as the batteries. **Figure 4-4** depicts the reduction of the solar panel size and the consumed power in terms of reduction percentage compared to the values obtained where two BSs were considered to be always active as a function of the estimated traffic evolution in 5 years, see details in [18]. Battery size is linearly proportional to the solar panel size and, thus, the experienced reduction is the same in both cases and is not presented here. As it can be observed, for some locations (SC –Santa Clotilde, NU – Negro Urco, TP – Tuta Pisco, and SG – San Gabriel), the amount of reduction is around 15-20% for the first 5 years.

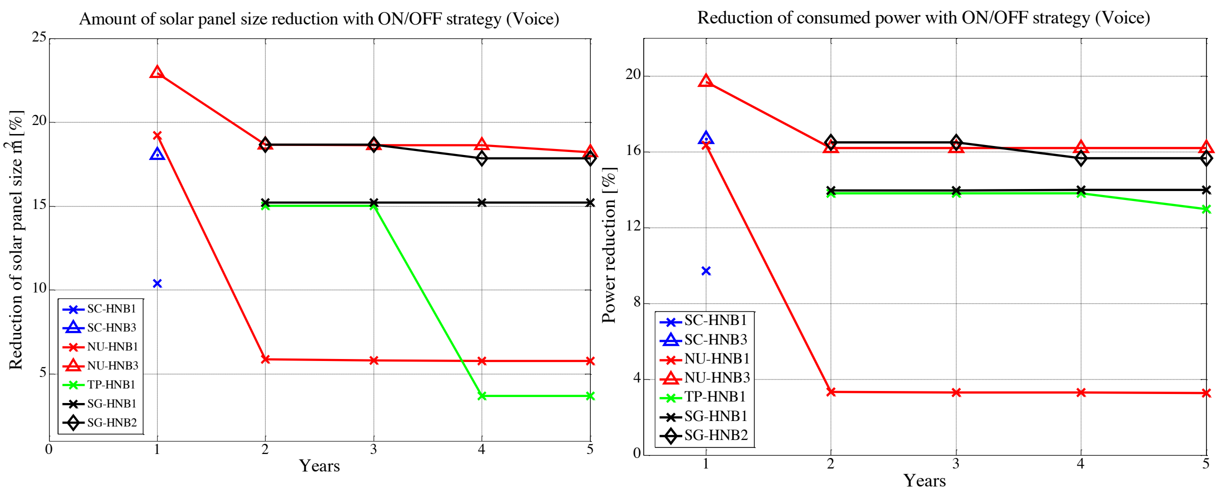

Figure 4-4: Left figure: amount of solar panel size reduction after on-off strategy. Right figure: amount of power reduction after on-off strategy. Results are given in percentage terms.

Now, we consider the design of a robust Bayesian switching threshold (denoted as $\lambda_{TH}^{'}$). **Figure 4-5** shows the threshold computed using the Bayesian methodology for a given variance of error modelling and for different outage probabilities (denoted as θ). We also show the deterministic threshold (when the traffic profile is perfectly known). We can see that, if we allow a higher outage probability, then the threshold increases. For the particular case of $\theta = 0$, the threshold should be set to zero, i.e., $\lambda_{TH}^{'} = 0$. Another effect that we can see and also expect is that for larger variances, we cannot trust the estimation and, thus, the threshold must be reduced to guarantee the same outage. We also see that for large variances, the outage probability does not have an important impact on the threshold calculation.

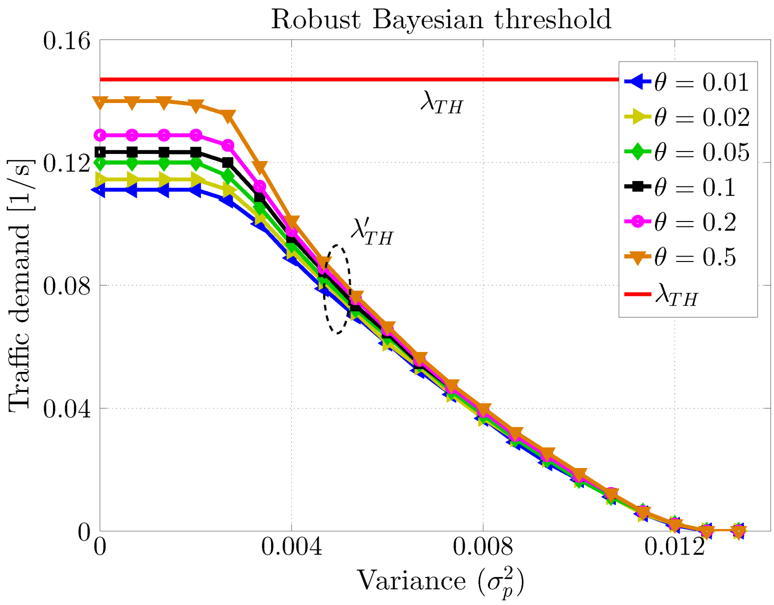

Figure 4-5: Bayesian threshold as a function of the variance of the error modelling σ_p^2 and different outage probabilities.

As concluding remarks, in this section, we have presented a methodology for switching on and off BSs that were solely powered with an energy harvesting source (e.g., solar panels) and a finite battery. The scenario under consideration was based on two BSs placed at the same site, with fully overlapped coverage areas and using two different frequencies. We proposed a decision strategy where we had perfect knowledge of the traffic profile and a robust Bayesian strategy in order to account for possible error modeling in the traffic profile information. Simulations were performed with real data for a real network deployment. Results showed that it was possible to reduce around 15-20% the size of the solar panels and the batteries.

4.1.3 User association for load balancing in heterogeneous networks with energy harvesting transmitters

Heterogeneous networks (HetNets) have emerged as a potential solution to increase the system throughput in order to meet the surging traffic demands [19], [20]. In particular, there is a strong tendency to consider the deployment of small BSs, such as for example, picocells and femtocells, along with already deployed macrocells. Each of these different types of BSs differ substantially in terms of maximum transmit power, physical size, and cost among others. As we are targeting rural scenarios where only energy harvesting devices will empower the BSs, each particular type of BS will also differ in terms of energy requirements, e.g., battery size and energy harvesting source. If solar energy is considered, the latter basically means to have different solar panel sizes. HetNets enable a more flexible and economical deployment as new infrastructure can be deployed as it becomes necessary. Moreover, small cells are usually easier to install and, thus, it reduces the deployment cost.

HetNets composed of several types of BSs are usually known as multi-tier networks, where each tier is represented by a type of BS [21]. Thanks to having smalls cells deployed within the coverage area of macrocells, traffic offloading techniques can be implemented by dynamic association of some of the users to the small cells and, thus, improve the overall network throughput. The well-known user association considered in 3GPP standard is based on received maximum SINR. Nevertheless, such approach does not provide fair load balancing as users tend to connect to the strong BS (usually the macrocell) and, thus, it becomes heavily loaded. As a consequence, a user association strategy that manages such user associations with the goal of introducing load balancing is needed. More importantly, if the BSs are only powered with batteries, then the battery status as well as the harvesting capabilities need to be considered in the association strategy; otherwise the best BS will run out of energy very quickly. By best BS, we mean BSs that can provide larger data rates.

There are a few works in the literature dealing with the concept of user association for load balancing. However, most of them only consider macrocell networks (see for example [22], [23], [24], [25]) and just the latest papers focus on HetNets scenarios. Concerning solutions for HetNets, authors in [26] propose a solution for cell association managing the interference being generated among BSs in a LTE-like setup scenario. They propose simple heuristic techniques that showed a significant improvement in the system performance. In [27], authors propose a downlink cell association based on dual coordinate descent method. Such methods have a convergence speed higher than gradient-like conventional methods usually employed. User association for load balancing is addressed in [28]. In that paper, the authors proposed a load measure based on user long-term service data rate. They also introduce biasing methods for cell range expansion. There are also some other works within the framework of stochastic geometry, see for example [29]. On the other hand, there are a few works that present joint resource allocation and cell selection mechanisms. For example, in [30] the joint resource allocation and BS assignment design is considered under the setup of CDMA networks. They develop a pricing-based distributed algorithm that considers congestion level of the BSs as well as the transmission environment of the mobile terminals. Authors in [31] study the joint BS association and resource allocation in downlink OFDMA networks. They propose a computationally tractable strategy-proof mechanism that is approximately optimal in terms of throughput. Finally, in [32], a distributed resource allocation and BS selection is proposed for the uplink setup in HetNets.

However, none of the previous works have considered the base stations to be powered with a battery and an energy harvesting source as we do in this work. In this section, we introduce a user association strategy that performs load balancing among the different network tiers and that considers implicitly the battery status of the BS as well as the energy that is being harvested.

Let us consider a downlink scenario composed of several BSs. Each of these BSs belongs to a particular BS class each having different capabilities (transmission power, battery size, etc) where each class is categorized as a tier. There are two different set of users in the systems, voice users, which request a fixed data rate service, and data users, which request a variable data rate service. Without entering into too much detail, the load balancing procedure that we propose can be modelled with the following convex optimization problem

$$
\begin{aligned}
&\underset{\bar{\mathbf{P}},\,\mathbf{P},\,\mathbf{n},\,\mathbf{x}}{\text{maximize}} && \sum_{j\in \mathrm{U}_D} U_j\left(\sum_{i\in \mathrm{B}} n_{ji}\log_2\left(1+\frac{M_D\bar{P}_{ji}}{n_{ji}\left(\theta_j P_{\mathrm{BS}}^i + A_{ji}\right)}\right)\right)\\
&\text{subject to} && C1:\sum_{i\in \mathrm{B}}\frac{M_V P_{ji}}{\theta_j P_{\mathrm{BS}}^i + A_{ji}} \ge \gamma_j, \quad \forall j\in \mathrm{U}_T\\
& && C2:\sum_{i\in \mathrm{B}} x_{ji} = 1, \quad \forall j\in \mathrm{U}_T\\
& && C3:\sum_{j\in \mathrm{U}_D} n_{ji} \le n_D^{(i)}, \quad \forall i\in \mathrm{B}\\
& && C4: T_e\left(\sum_{j\in \mathrm{U}_D}\bar{P}_{ji} + \sum_{j\in \mathrm{U}_V} P_{ji}\right) \le \phi_i\left(B_i\right), \quad \forall i\in \mathrm{B}\\
& && C5: 0\le n_{ji} \le x_{ji} n_D^{(i)}, \quad \forall i\in \mathrm{B}, \forall j\in \mathrm{U}_D\\
& && C6: 0\le T_e P_{ji} \le x_{ji}\phi_i\left(B_i\right), \quad \forall i\in \mathrm{B}, \forall j\in \mathrm{U}_V\\
& && C7: x_{ji} = 0, \quad \forall i\notin \mathrm{S}\left(j\right), \quad \forall j\in \mathrm{U}_T\\
& && C8: x_{ji} \ge 0, \quad \forall i\in \mathrm{B}, \forall j\in \mathrm{U}_T\\
& && C9: \bar{P}_{ji} \ge 0, \quad \forall i\in \mathrm{B}, \forall j\in \mathrm{U}_D
\end{aligned}
\tag{4.1.2}
$$

The main idea behind the previous optimization problem is that we use estimated values of power, number of codes (we consider a WCDMA system), and rates to characterize the load of a given BS. The objective is to maximize the sum of a general function of the data rate with constraints on the power, the number of codes, the fixed data rate service for voice users, and constraints on the association variables x_{ji}. For the specific models of power consumption and harvesting, and the assumptions made in the constraints, please see [33]. The approach to solve the previous problem is based on a primal-dual decomposition technique. Such technique also allows for a distributed implementation, i.e., users decide to which BS they want to connect to and so just local information (in terms of channel state, battery state…) is required to make such decision.

In terms of the numerical evaluation, we compare the proposed user association technique with the traditional maximum-SINR approach, where the users just measure the received pilot power and select the BS with the strongest value. For the specific simulation parameters and the architecture of the deployment, please refer to [33].

Figure 4-6 shows the CDF of the individual rates but studying the effect of having different harvesting capabilities and different α values (such α value appears in constraint C4 of (4.1.2) in the definition of the function $\phi(\cdot)$ and is basically the fraction (between 0 and 1) of the battery that is allowed to be used for radiation, see [33]). In the legend of the figure, MS stands for max-SINR and G for the proposed approach. As we can see if the harvesting is larger, i.e. for larger values of the harvesting intensity p, the curves tend to shift to the right, which means that a more balanced network is achieved. The performance for different values of α is not quite different and practically negligible for larger harvesting, but we can see that smaller values of α provide a better load-balanced network. Note that $a = 1$ allows the BS using all the battery at each particular epoch.

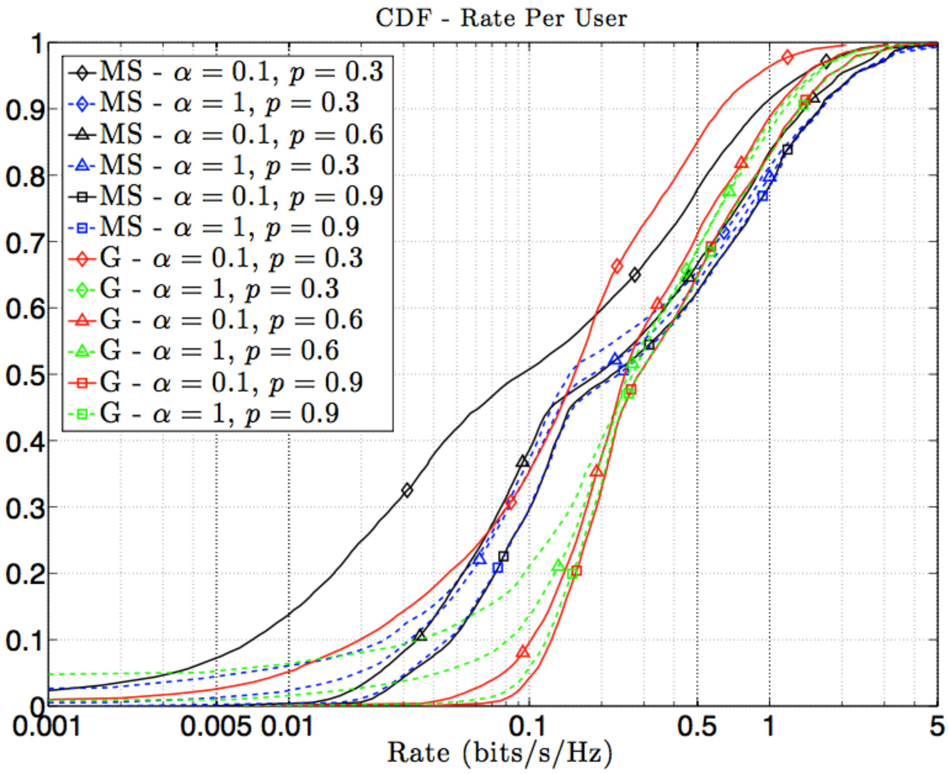

Figure 4-6: CDF of individual user rates for different harvesting and values of α .

In the following figures, **Figure 4-7** and **Figure 4-8**, we depict the evolution of the battery level for the different tiers considering different values of α and harvesting (averaged among BSs belonging to the same tier). As we can see from the figures, if $\alpha = 1$ the residual battery level is quite low, except for the case of the tier 4. What happens in such case is that there are no users to be served in this tier and thus the battery keeps increasing. The difference between the max-SINR policy and the proposed general case (MS and G in the legend, respectively) is irrelevant and almost non-existent.

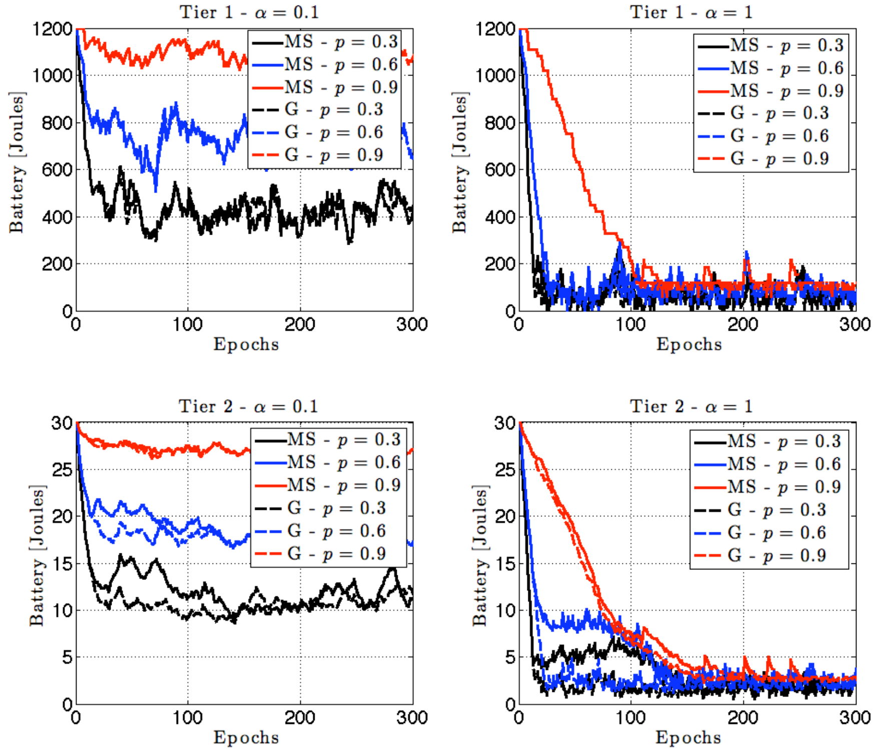

Figure 4-7: Average battery evolution (among BSs) of tier 1 and tier 2.

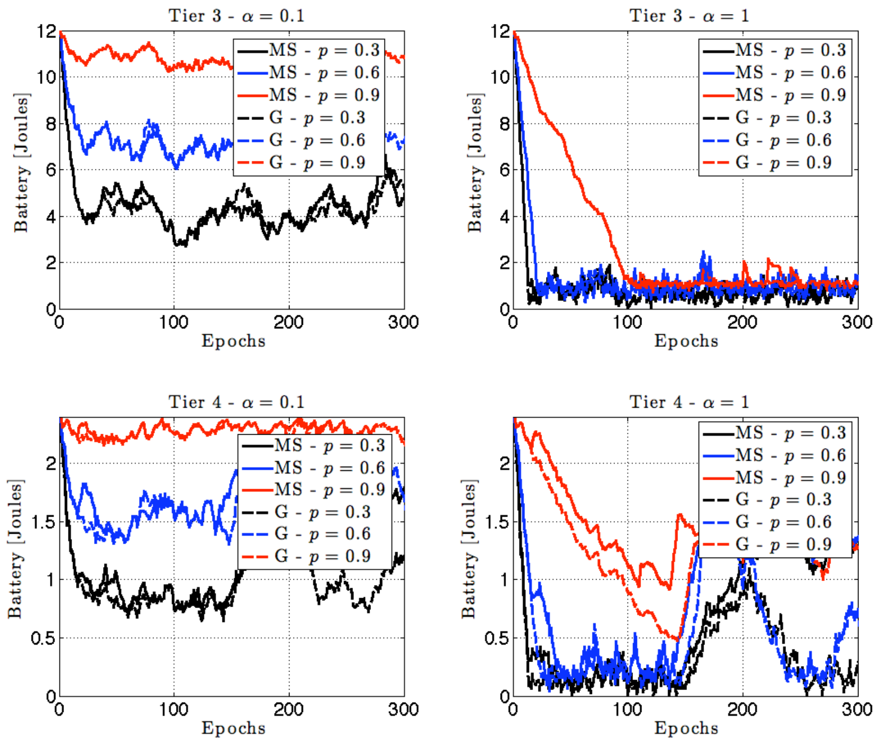

Figure 4-8: Average battery evolution (among BSs) of tier 3 and tier 4.

Results concerning the evolution of the number of users among the different tiers over epochs as well as other important simulation results are omitted here for brevity but are available in [33].

In conclusion, in this section we have proposed a user association strategy to achieve load balancing in heterogeneous networks where the BSs were solely powered with finite batteries and energy harvesting sources that allowed the BSs to recharge their batteries. An iterative solution based on a primal-dual approach was derived. We have compared the proposed strategy with the classical max-SINR approach and showed that improvement is possible if the information of the battery status is considered in the user association procedure.

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4.2 Achievements JRA 1.3.1B – Signal support detection

In this activity, first we addressed the problem of distributed support detection of multiple sparse signals with common support. Specifically, we have considered a distributed setting by which signals are acquired by the individual nodes of a network. In this scenario, we have proposed a decentralized scheme, referred to as Distributed iterative Thresholding (DiT), for in-network support detection. The approach is reminiscent of the iterative soft and hardthresholding methods. DiT has been proved to converge and the numerical results have revealed that DiT achieves consensus in the signal support in most of the cases.

Next, in the same distributed setting, we have considered the case where the observed signals are correlated. In particular, we have assumed that the observed signals are composed of a common sparse component plus an innovation sparse component. First, we have developed a centralized solution based on the Alternating Direction Method of Multipliers (ADMM). Then, we have proposed a distributed version for in-network reconstruction called DADMM. Finally, in order to reduce the amount of information exchanged that such distributed approach entails, we have also proposed a novel scheme only requiring binary message exchanges among neighboring nodes called DADMM-1 bit.

Numerical results have revealed that, after convergence, the proposed distributed algorithms perform virtually identical to the centralized ADMM. More importantly, the DADMM-1 bit only requires 3 times more iterations to converge than the DADMM.

4.3 Achievements JRA 1.3.1B – Distributed SPS algorithms for parameter estimation in sensor networks

4.3.1 *Description*

This work considers the distributed computation of non-asymptotic confidence regions in wireless sensor networks. We proposed a distributed alternative of the Sign-Perturbed-Sums (SPS) algorithm, originally proposed for centralized networks [2,4].

To ensure that the confidence region computed by each node is similar in shape to the one that would be evaluated in a centralized setup (e.g., via flooding techniques [1], [3]), nodes having initially access to local quantities have to share information with the other nodes in the networks. Sharing information is, however, costly in terms of generated traffic load and, in general, not scalable with the size of the network. Moreover, the need to reduce energy consumption as much as possible, is a crucial aspect for WSNs.

This consideration suggested us to investigate a novel information diffusion strategy, denoted Tagged and Aggregated Sums (TAS) that, exploiting the peculiarities of the SPS algorithm, allows a reduction of the amount of information to be exchanged among nodes. Its performance is compared to that of classic information diffusion strategies, such as flooding and consensus, in terms of generated traffic load as well as confidence region volume/traffic trade-off. Both analytical models for performance predictions and simulation results on various topologies are provided.

In view to further reduce the transmission costs, we also investigated whether non-asymptotic confidence regions can still be derived with SPS when the information diffusion process is truncated, before its completion, because of traffic, energy or delay constraints. A theoretical framework has been thus developed, proving that consistent non-asymptotic confidence regions can still be computed by nodes, starting from an incomplete set of measurements.

4.3.2 *References*

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4.4 Achievements JRA 1.3.1B – Distributed outlier detection in wireless sensor networks

4.4.1 Description

The presence of defective sensors producing outliers may compromise the global behavior of a WSN dedicated to distributed estimation. In this work we have designed a low-complexity, distributed fault detection (DFD) algorithms, well adapted to the absence of central processing unit and to power constraints typical of WSN. Each node is able to decide about the state of its measurement unit (normal / faulty) and react accordingly (e.g., powering off or acting only as communication router if defective).

Set-membership estimation techniques are employed to detect the presence of outliers [8]. If a set of measurements collected by a node from its neighborhood is corrupted by an outlier, the set estimate is likely to be empty. In absence of outlier, the set estimate cannot be empty. This outlier detection technique is thus well adapted to distributed group testing, and isolation of faulty sensors, as illustrated in some preliminary work [1] done in collaboration between CNRS/UPSud and CNIT/Bologna.

We have proposed an iterative outlier detection algorithm. To evaluate its behavior and prove its convergence and stability, we have accurately modeled the behavior of the outlier detection technique involved at each step of the algorithm as a function of the number of valid measurements, outliers, noise, and propagation characteristics. With this model and spatial models of node distribution, one is able to perform a theoretical analysis of the fault detection accuracy and of the false alarm rate using tools borrowed from stochastic geometry tools.

The second objective is to deploy the outlier detection technique on the EuWIn@CNIT/Bologna platform DATASENS. The algorithms proposed in [1] have the advantage of allowing a relatively simple implementation. This will allow an experimental verification of the theoretical results we plan to develop.

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4.5 Achievements JRA 1.3.1D – Energy-efficient Adaptive Modulation and Coding for CSMA Networks

In the first joint study, we proposed a cross-layer energy-optimum adaptive modulation and coding policy (CLEO). The proposed policy improves energy consumption by adapting its aggressiveness according to the network congestion. In a highly congested CSMA network, a node needs numerous carrier sensing attempts to capture the channel. These repeated sensing attempts consume energy along with the energy consumed during idle waiting between the transmission attempts. For that reason, CLEO becomes more conservative in a highly congested scenario. On the other hand, if the network is not congested, CLEO becomes less conservative since the node will capture the channel in fewer attempts which will reduce the energy cost of a retransmission.

The proposed cross-layer policy (CLEO) improves energy consumption in comparison to a single-layer policy (SL) as it can be seen in Figure 4-9 for a vehicular channel with time-varying SNR. The cross-layer policy is more conservative in selecting a modulation and coding scheme (b) and reduces the energy consumption as a result (c). On the average it is possible to improve energy consumption 20% with respect to a single-layer policy for typical energy consumption parameters in a highly congested network.

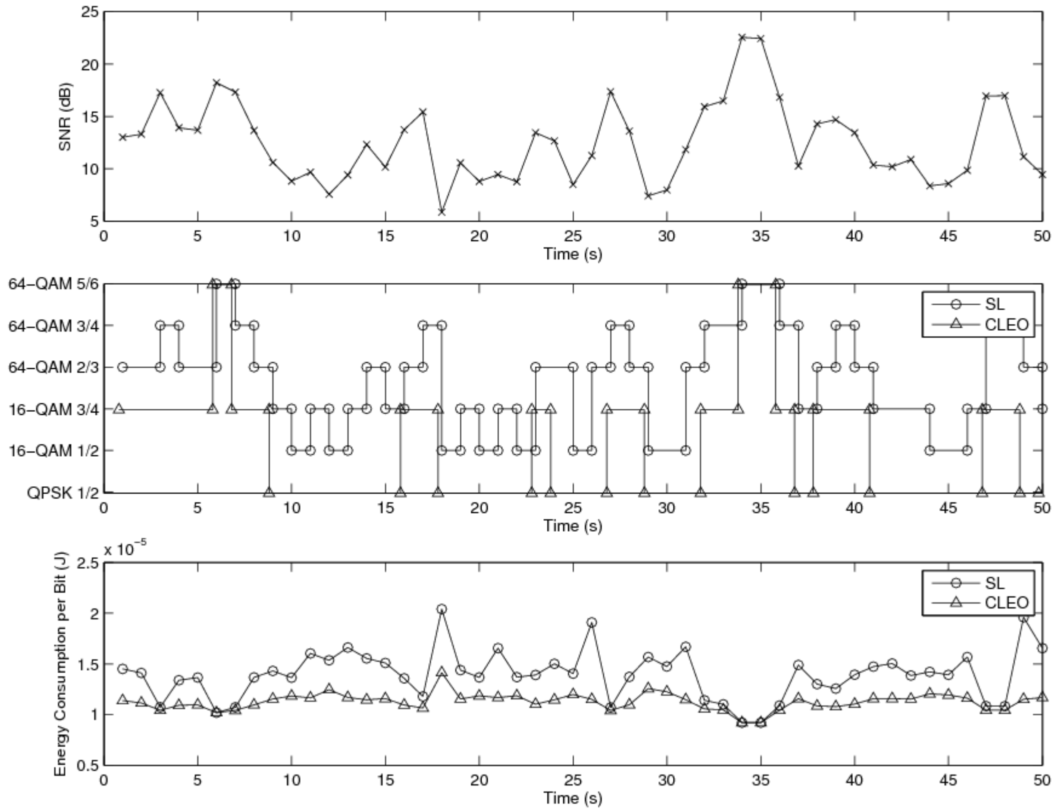

Figure 4-9. (a) The time varying SNR behavior in a vehicular channel. (b) Behavior of the single layer policy (SL) and the proposed cross-layer policy (CLEO) (c) Energy consumption per bit obtained by each policy.

We have also investigated the effect of idle power consumption (P_i) and the network load (G) on the energy efficiency gains obtained by the proposed policy. Figure 4-10 plots the gains obtained by CLEO as P_i increases for different network loads. The performance of CLEO improves as P_i and G increases. As G increases, the number of sensing attempts to capture the channel increases which in turn increases the energy consumption. As P_i increases, the energy consumption during idle waiting caused by retransmissions increases. For that reason, a cross-layer policy becomes more conservative as P_i and G increase and the improvement obtained in comparison to SL increases (Figure 4-10).

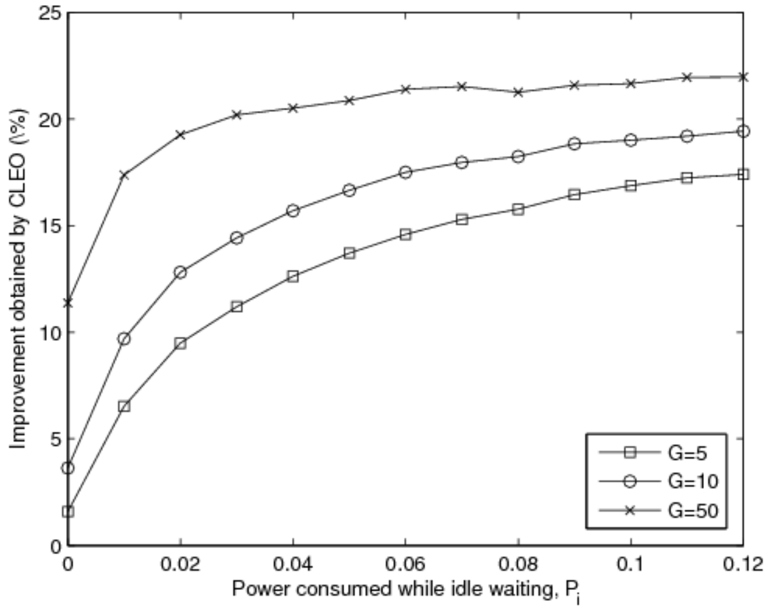

Figure 4-10. Energy efficiency gains obtained by the proposed policy as the power consumed while idle waiting increases for different network loads (G).

In the second joint study, we have investigated the cross-layer optimization of acoustic underwater networks. Our results show that a higher MAC layer throughput and a lower physical layer throughput should be allocated to a node as its distance increases to the base station. When a node's distance to the base station increases, its physical layer efficiency decreases significantly. For that reason, it is better to increase the MAC layer throughput of a distant node instead of allocating a higher physical layer capacity. Figure 4-11 shows how the optimum physical layer capacity and attempt rate of a node changes as its distance to the base station increases. Different plots in the figure shows the fairness index constraints for the throughput distribution among the nodes.

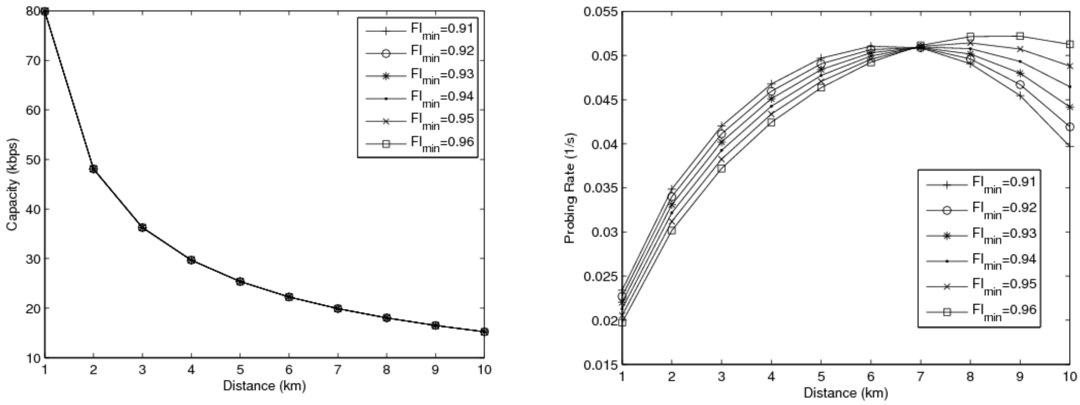

Figure 4-11. The capacity and the attempts rates allocated by an energy-optimum scheme.

4.6 Achievements JRA 1.3.2A – Study on the impact of multi-tap filtering in FBMC/OQAM systems and on the margin adaptive scheduling in multi-user FBMC/OQAM systems

4.6.1 Description

Due to the advent of increasingly rate demands, cellular systems densify their cell deployment and become more heterogeneous to satisfy the upcoming needs. Thus, different wireless communication systems may co-exist in the same geographical area. This leads to the increase of the interference. To circumvent this problem to some extent it is of paramount importance to achieve a fine grained control of the spectrum. The dominant technology is the orthogonal frequency division multiplexing (OFDM) modulation scheme, which is able to partition the transmission bandwidth into narrowband subchannels. However, OFDM exhibits poor stopband attenuation, which makes this modulation sensitive to synchronization errors and narrowband interference. Hence, OFDM may be unsuitable to satisfy the upcoming needs. In this sense, the filter bank multicarrier modulation based on offset QAM (FBMC/OQAM) is a potential substitute of OFDM [1,2]. The main asset of FBMC/OQAM stems from the fact that subcarriers can be shaped with well-frequency localized waveforms, thus increasing the robustness of the system against time and frequency misalignments. In addition, the maximum bandwidth efficiency is obtained since no redundancy in the form of a cyclic prefix (CP) is transmitted. It must be mentioned that this merit comes with the price of relaxing the orthogonality conditions, so that perfect reconstruction of the transmitted signal is only satisfied in the real domain. This means that multipath fading may destroy the orthogonality between subcarriers leading to inter-symbol and -carrier interference. As a consequence, the signal processing techniques that aim to combat the propagation conditions originally designed for OFDM cannot be directly applied to FBMC/OQAM in general. This highlights the necessity of taking into account the transmission modulation format when designing the subband processing. For this reason, there are some research areas that are not sufficiently explored when the FBMC/OQAM modulation scheme is considered, for instance, the study of equalization techniques in presence of highly frequency selective channels and the design of schedulers. In the following we detail the contribution that has been made regarding the aforementioned topics.

Concerning the equalization techniques especially though for FBMC/OQAM, the literature is quite extensive, see e.g. [3-8]. When the frequency selectivity of the channel becomes appreciable at the subcarrier level, multi-tap filtering is required to compensate the channel. Otherwise, orthogonality is destroyed and residual interference terms may significantly degrade the performance. Unfortunately, the application of multi-tap filtering to FBMC/OQAM systems may be responsible for boosting the power or enhancing the noise power, depending if the channel is compensated either at transit or receive side. To shed some light into this issue we have characterized in [9] the average transmit power and the average noise power, when the channel is pre-equalized at transmission and equalized at reception, respectively. From the closed-form expressions derived in [9], we conclude that if the transmit power increases/decreases, then the noise variance increases/decreases as well with the same magnitude, as long as the same filters are used as precoders or equalizers. This reveals that if the transmitted symbols are properly scaled when the transmit processing boosts the power, then there is no degradation due to equalizing the demodulated data instead of precoding the symbols to be transmitted.

The applicability of FBMC/OQAM to multiple-input-multiple-output (MIMO) systems is a non-trivial task due to the intrinsic interference that is inherent to the FBMC/OQAM modulation scheme [1,2]. The problem is even more challenging when multiple users are allocated to the same frequency resources, because the received signal is affected by inter-symbol, -carrier and -user interference. In this regard, the authors in [10] have made some progress towards the combination of MIMO and FBMC/OQAM in multi-user communication systems. Building upon the MIMO precoding and decoding matrices designed in [10], we have addressed in

[11] the resource allocation problem. In particular, the work presented in [11] aims at minimizing the transmit power in the downlink subject to users' rate constraints, by jointly designing the transmit and receive beamforming, the channel assignment and the power allocation. It has been demonstrated that if subcarriers are assigned to users in a block-wise fashion we can exploit spatial diversity to allocate several users in the same frequency resources in the absence of interference. Then, benefiting from the work derived in [12] it is possible to efficiently solve the resource allocation problem resorting to linear programming. Numerical results have shown that since no energy is wasted in the FBMC/OQAM modulation scheme, this modulation is able to transmit the same amount of information as OFDM but using less power.

4.6.2 References

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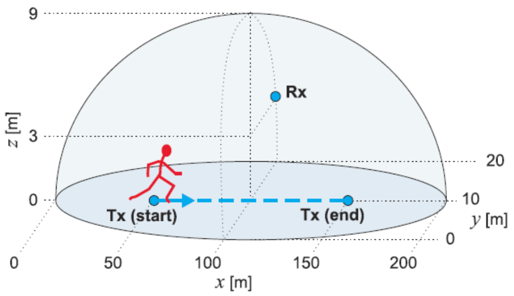
4.7 Achievements JRA 1.3.2.A – Application of the MISO-OFDM scheme in the body area networks

4.7.1 Description

In this section we present the concise summary of the results presented in [1].

For many years, the role of wireless solutions in the area of telecommunications is continuously increasing, and in many aspects the technology can be stated as mature. Recently, rich literature delivers great variety of possible applications or Body Area Networks (BANs), such as integration of this kind of network with intelligent clothing. The concept of application of everyday clothing for communication purposes has been already realized in bigger or smaller ranges in practice (e.g. intelligent glasses [2], safety-focused jackets [3], overcoats equipped with tunable radio [4]). An application of clothes for communications improvement is one of the research directions for wireless BANs, since in many situations the quality of the wireless link between the mobile device and the network (of any kind) is below the acceptable level. One can consider such a scenario, when a big number of wearable antennas will be deployed on the human body and used as ad-hoc Multiple Input Multiple Output system for improvement of overall system performance. In order to make this observation more instantiated one can consider the military example, where soldiers wear intelligent clothes with multiple antennas and transmit video signals (and other data) to their headquarters during reconnaissance or patrol. Wireless cameras connected to the antennas will then transmit the low-power signal in a continuous manner. Let us notice that the deployment of antennas on-body is reasonable in the light of recent developments (e.g. the announcement of new wearable textile antennas presented in [5]). Moreover, it is quite feasible to keep the physical distances between the antennas above the required minimum distance. In this work the application of bit and power loading [6] algorithm for MIMO-OFDM with Transmit Antenna Selection scheme has been considered.

In the first step, the detailed channel model (including voxel model of human body) has been investigated and applied [7]-[9] to be tested in two scenarios – run-straight (where the female human runs straight over the distance of tens of meters) and run-loop (when the same female human runs in circle). These scenarios are presented in Figure 4-12. Eight antennas have been mounted on human body, as illustrated in Figure 4-13.



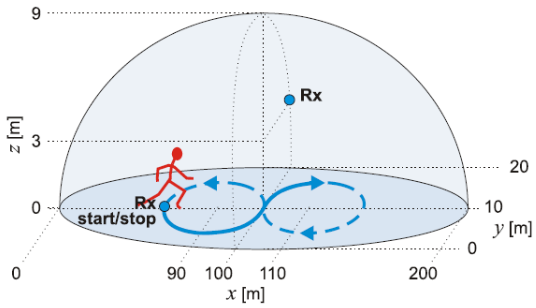


Figure 4-12. The run-straight (left) and run-loop (right) scenario

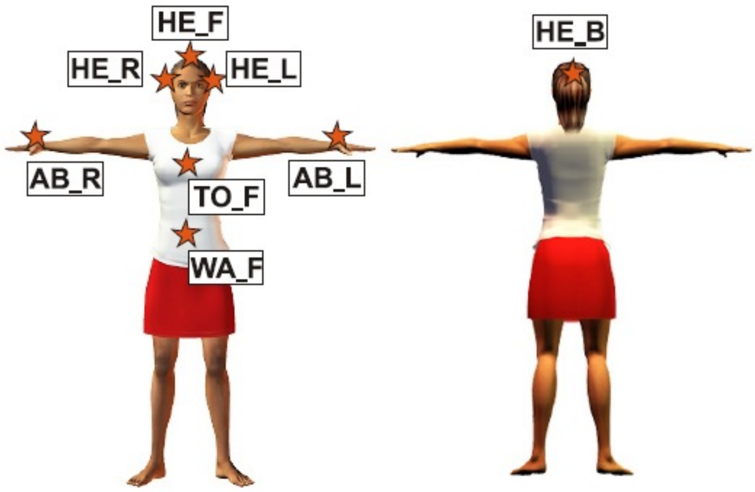


Figure 4-13. Location of the antennas on the body.

In the extensive computer simulations various parameters have been checked and investigated. First of all, it has been identified that there is direct influence of the antenna location on body on the observable path loss values. Namely, the maximum difference in the observed path loss values is equal to 56 dB, whereas on average the difference between the maximum and minimum value of path loss among the eight selected antenna positions is equal to 23 dB. In consequence, the differences in SNR values observed on each antenna differ often quite significantly, leading us to the conclusion that the application of transmit antenna selection scheme could be beneficial. Finally, the averaged achievable rate has been analyzed, and the achieved results are presented in Figure 4-14. Please let us note that in the applied bit and power loading scheme the maximum constellation order was set to 6 (i.e. 64 QAM). One can observe that the average rate reaches the theoretical limits. Such results prove the validity of the concept that BAN networks applied in form of ad-hoc MIMO can lead to the improvement of link performance.

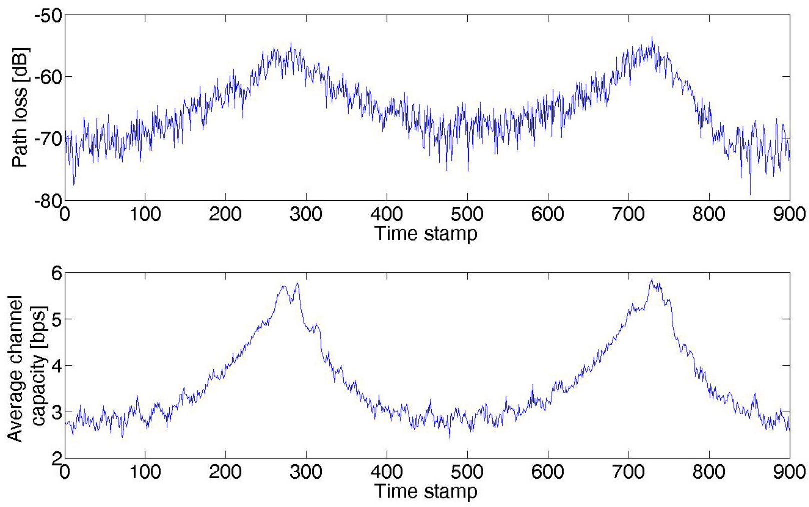


Figure 4-14. Achieved averaged path loss (upper figure) and averaged rate (bottom figure) for the run-loop case

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4.8 Achievements JRA 1.3.2.B – Primary user aware spectrum shaping for interference reduction in NC-OFDM systems

4.8.1 Description

This activity resulted from the consideration of a Non-Contiguous OFDM (NC-OFDM) system that has to coexist with a Primary User (PU) system, which in our case is represented by the Wireless Microphone (WM), although it can be extended to other types PUs. While developing a new radio transmitter the designers have to keep the power emission requirements specified in form of a given Spectrum Emission Mask (SEM). In this work it was observed that important role is not played by the Out-of-Band (OOB) radiation generated in the band of PU (e.g. 200kHz in case of wireless microphone) but the overall interference power observed by the WM receiver (i.e., after passing WM reception chain). While knowing the Power Spectral Density (PSD) of the transmitted signal it is possible to utilize results of the PU receivers' measurements made by e.g. OFCOM [1] in order to estimate the interference power observed in the PU receiver.

In the case of NC-OFDM modulation there is a number of techniques available in the literature that tackle this practical problem. During the second project year, the Cancellation Carriers (CCs) technique that had been improved previously [2] was further investigated. The selection of this solution is motivated by its acceptable computational complexity as well as high OOB radiation attenuation abilities in comparison to other CCs-based algorithms previously proposed in the literature. The cancellation carriers create a specially chosen set of data subcarriers that is used for reduction of the OOB power caused by subcarrier spectrum sidelobes of data carriers. Being a reasonable and successful outcome of this activity, a computationally efficient method of calculating CCs values in order to minimize the interference power in the PU receiver has been proposed. Achieved results originated form this work have been recently presented at EUSIPCO 2014 [3], moreover, the modified version of that solution with reduced computational complexity at KKRRiT 2014 (Polish conference) [4]. An example of the results can be seen in Figure 4-15 and Figure 4-16. The normalized PSD plots show, first, that guard subcarriers method does not provide either OOB radiation or interference power reduction to a sufficient level. On both plots it is notable that optimized CCs selection (OCCS) outperforms traditional CCs selection.

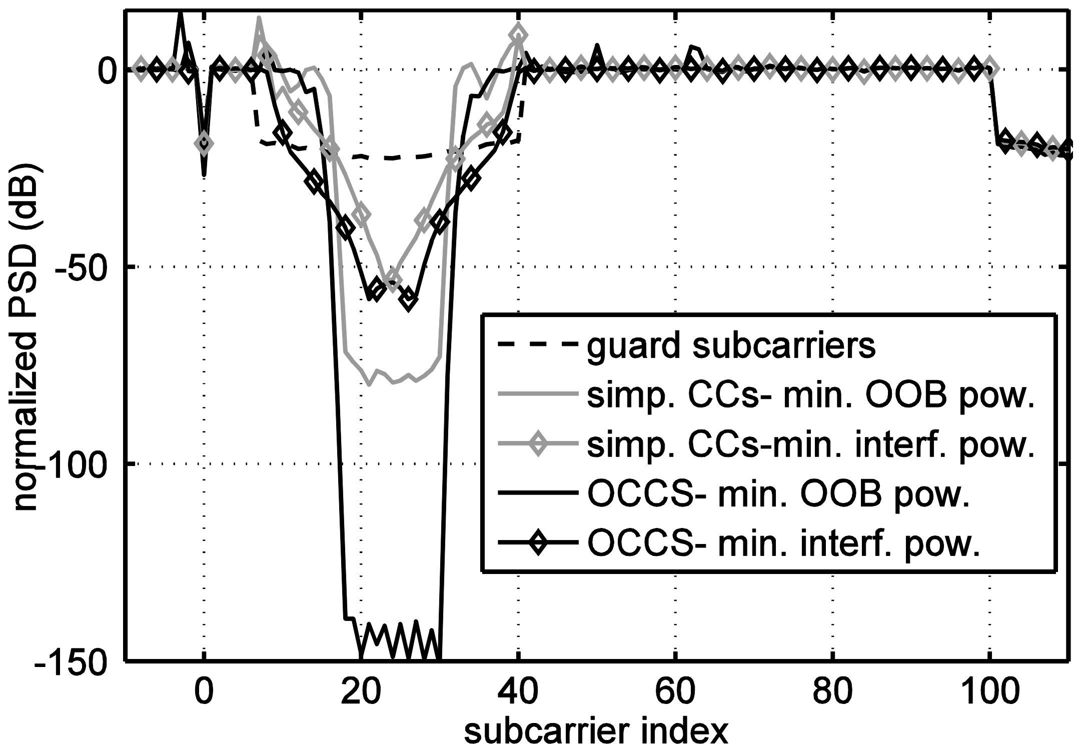

Figure 4-15 Normalized PSDs before PU reception chain (166 data carriers, 34CCs)

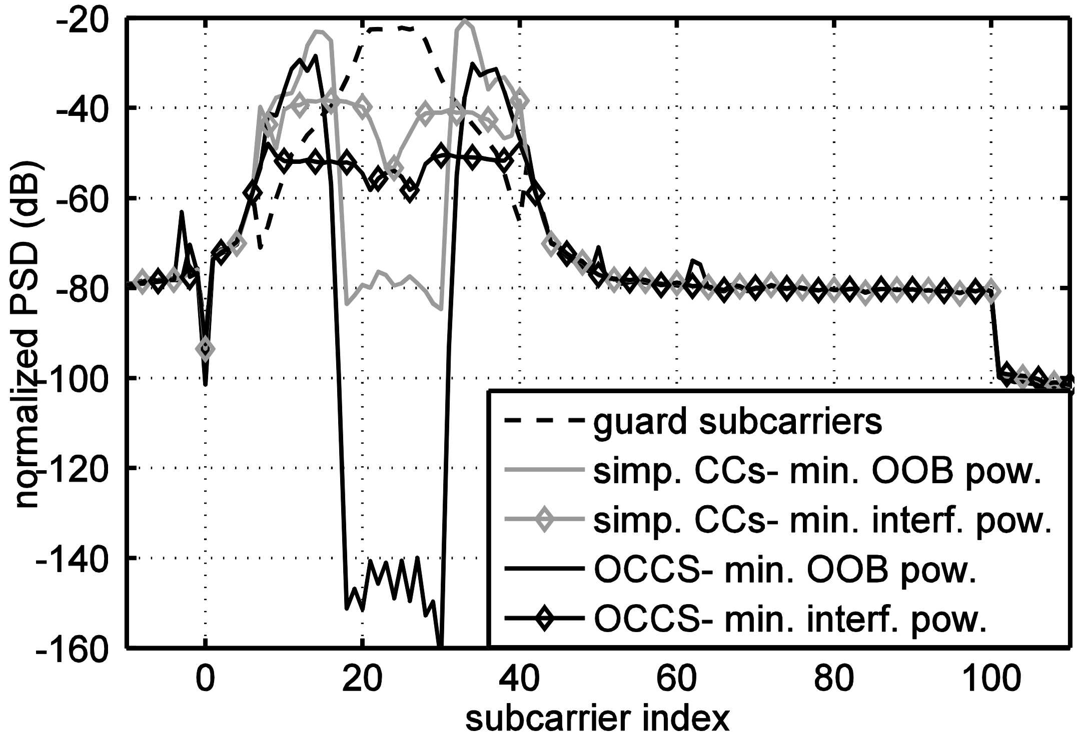

Figure 4-16 Normalized PSDs after PU reception chain (166 data carriers, 34CCs)

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4.9 Achievements JRA 1.3.2.B – Analysis of NC-OFDM PAPR distribution

4.9.1 Description

In order to design efficient Peak-to-Average Power Ration (PAPR) reduction scheme in NC-OFDM system proper modeling of this metric is required. Carrently, no accurate description of this phenomenon can be found in the literature when referring to the non-contiguous multicarrier solutions. PAPR reflects the amplitude variation of the time domain signal that will be amplified in the transmitter chain. The higher the PAPR value, the higher the amplitude of the time domain sample and, in consequence, potentially higher out-of-band power emission. Typically, when referring to the OFDM systems, the characteristics of PAPR is derived based on approximation of the Gaussian distribution, however this is only valid when the number of samples is high.

Within this activity both theoretical and simulation-based results were obtained from the perspective of non-contiguous multicarrier systems. The considered test scenario is a NC-OFDM signal constituted of two sets of continuous subcarriers. As each set utilizes a relatively high number of subcarriers, an approximation by Gaussian distribution can be justified in this case as well. Although the initial results have been obtained for two blocks separated by the gap of unused spectrum, the proposed derivations can be easily extended to the scenario with three, four or more sets of continuous subcarriers.

From the theoretical perspective Gaussian distribution allowed to provide upper bound of PAPR distribution (much closer to the maximum PAPR value provided in [1]). Based on that approach and utilizing the triangle inequality, the closed-form formulas describing these bounds have been defined, however the evaluation of the proposed solutions still have to be done. It is worth noticing that from the simulation point of view, it was observed that single-band OFDM system obtains the lowest PAPR values. Additionally, it was observed that the value of PAPR depends on the shift between two occupied subcarriers blocks. The regularity observed in this behavior allows us to justify it by some determinant property of NC-OFDM modulation (e.g. correlation between subcarriers while oversampling is considered) rather than random result of the simulation process. Again, these findings are still subject of detailed investigation which will be the subject for further research in the third project year.

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4.10 Achievements JRA 1.3.3.A – REM-based architectural framework for supporting interference management in HetNets

4.10.1 Description

Recent years have witnessed an exponential growth of the demand for mobile broadband services associated with the massive penetration of wireless equipment as smartphones, tablets, etc. and the proliferation of bandwidth-intensive applications. This trend is expected to even increase in the future with novel applications involving High Definition Video, virtual reality, etc. Then, for a better provision of such high capacity demanding services the classical cellular network concept is being shifted towards the Heterogeneous Networks (HetNets) [1] composed of both large macrocells and small cells of different sizes such as picocells, femtocells, etc. They are expected to provide high capacity in densely populated areas and to provide additional coverage e.g. in indoor. HetNets can also involve other radio access technologies such as Wi-Fi that can contribute to offloading traffic from the cellular network.

The massive introduction of small cells in dense urban scenarios will necessarily require efficient coordination mechanisms to reduce inter-cell interference in case that the same frequency is shared between macro and small cells. For that purpose, Enhanced Inter-Cell Interference Coordination (eICIC) methods are considered. Different techniques exist that can be classified as frequency domain techniques, time domain techniques and power control techniques [2]. In frequency domain techniques, orthogonal transmissions of different users are achieved by assigning different frequency resources to the users in the different cells that can potentially interfere. In time domain techniques, the users that suffer from interference are assigned resources in specific time periods where the interference is suppressed. Finally, power control techniques adjust the transmitted power to reduce the interference generated to the victim users. In addition to this, a proper user-to-cell association also plays a key role to ensure that the users are connected to the most convenient cell and correspondingly they generate/receive less interference from the other cells. Moreover, when considering cellular and Wi-Fi networks (or other non-3GPP networks), it is also possible to reduce the interference in the cellular network by offloading traffic to the Wi-Fi network. This usually relies on the application of Access Network Discovery and Selection Function (ANDSF) and of the solutions proposed for so-called Hotspot 2.0 [3].

Given the randomness associated to propagation effects, user mobility or traffic generation, the development of optimized eICIC techniques requires a proper knowledge about the environment where HetNets are deployed. In this direction, the term Radio Environment Map (REM) is used to refer to a database that dynamically stores different types of information about the environment where a cognitive radio system operates [4]. It includes, among others, information about the propagation conditions, the transmitters in the area and their parameters, traffic density, etc. The knowledge contained in the REM can be exploited for the optimization of wireless networks, as in [5] where different applicability areas of the REM concept in cellular networks were identified. Then, JRA 1.3.3.A advocates for the use of REMs as a support tool in the optimization of eICIC techniques for HetNets and for supporting the traffic offloading to other networks, and proposes a REM-based architecture for supoorting such techniques.

A REM functional architecture was proposed in [6], where the REM is composed of four main entities, namely (i) Measurement Capable Devices (MCDs), which represent the network elements capable of performing measurements (e.g. terminals, sensing devices, etc.), (ii) REM data Storage and Acquisition unit (REM SA), which stores the data coming from the MCDs and the further processed data, (iii) REM manager, which is in charge of requesting measurements, extracting and processing the data from the REM SA, and (iv) REM user, which represents the entities using the REM data, such as resource management entities or policy managers.

The mapping of REM functionalities to specific network elements is tightly associated with the architecture of the wireless network considered. For example, in a 3GPP LTE architecture [7] and the REM applied to femtocell management, it is proposed in [6] that the REM Acquisition functionalities are included in the femtocells also denoted as HeNBs (Home evolved Node Bs) while the REM Manager and Storage functionalities are associated to the

HeNB Management System (HeMS) that controls the different femtocells. In turn, from a more general perspective including also macrocells or evolved Node Bs (eNBs), the architecture proposed in [5] considers a layered REM composed of several instances of the same REM functional architecture located at different nodes of the network. These layered instances facilitate scalability given that each REM entity only contains information about its local environment. Each layer may include only a subset of the REM functionalities, depending on the considered application. The upper level in the hierarchy is the REM entity at the network management subsystem of the operator. Below, the REM entity can be included in the Mobility Management Entity (MME) entity, in the eNBs, in the HeNB GateWay (HeNB GW) or even in the terminals.

The REM concept can be also applied for scenarios with various access technologies. The tight integration of cellular networks with Wi-Fi networks (or more in general the integration of 3GPP networks with non-3GPP networks) seems to be a meaningful solution to handle the exponentially increasing mobile traffic, since it allows offloading traffic from the cellular network and can thus contribute to reducing the interference. In this context REM can also contain information about the Wi-Fi network, served users, positions etc. allowing for efficient data offloading. Such scenario is of high importance when the deployment of integrated Femto-Wi-Fi (IFW) modules will be possible [8].

Taking as a reference the abovementioned approaches in the context of a LTE heterogeneous cellular network integrated with Wi-Fi access points, this JRA identifies different architectural possibilities for implementing REM-based interference coordination techniques. As the most general case, Figure 4-17 depicts a layered architecture in which each eNB and HeNB contains a local REM entity with information about its local environment, while the MME and HeNB GW contain global REMs comprising information at a large area level encompassing multiple eNBs and/or HeNBs, respectively. Although it is not depicted explicitly in the figure, each eNB/HeNB will include the functionalities of REM Acquisition to get the needed measurements to be stored in the REM. The global REM information may include some meta-information which can be generated based on the fine-granularity data retrieved from the local REMs in order to enable a macroscopic view and simplify some centralized decisions (e.g. highly loaded area, increase the offloading rate, etc.). Coordination between local REMs can be achieved either through the X2 interface or through the global REM and the S1 interface. With this layered approach, the local REM enables the support of resource management functionalities operating in short time scales while coordination (at a lower rate) can be achieved thanks to the global REM. In this way, this would be aligned with current trends of shifting most of the decisions and operations as close as possible to the user, so that associated latencies can be reduced.

When considering the integration between cellular and Wi-Fi networks (or other trusted/untrusted non-3GPP networks) for data offloading purposes, communication between the REMs managing only cellular users with the REMs either integrated with the Wi-Fi access point or IFW module, or REMs that possess the functionality of managing the Wi-Fi services, can be realized by means of pure IP connection and/or S2a/S2c interfaces, as depicted in Figure 4-17.

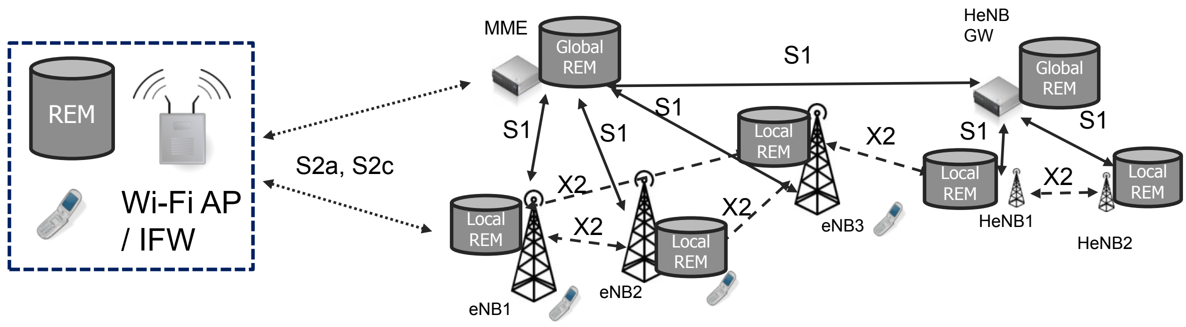

Figure 4-17: Layered REM architecture

Other possibilities can be derived from the general architecture of Figure 4-17. One option would be a totally distributed architecture with only local REM instances located at each eNB or HeNB and no global REMs. Coordination between REM instances could be achieved through the X2 interface to get information about the neighbour cells. This solution may be efficient from the REM storage and management perspective, since each REM only has to account for its local area. However, signalling associated to coordinating the different REM instances has to be taken into consideration depending on the rates at which information has to be updated, the amount of exchanged information, the computation and processing cost at each cell, etc.

Similarly, another option arising from Figure 4-17 would be the fully centralized approach with only global REMs at the MME and HeNB GW. In this approach, each REM will contain information about all the cells in the controlled area. This will facilitate coordination, but may involve large complexity and storage capability if the number of cells is large. Moreover, REM-based decisions may be executed at a lower rate than in the distributed or layered case because of the associated latencies to contact the REM. The coordination between the global REMs at MME and HeNB GW can be achieved through the S1 interface. Similarly, the possibility of having only the REM at the MME controlling both the eNBs and the HeNBs may also be considered, although this may not be efficient in case of a very large deployment of HeNBs.

Different eICIC techniques that can be supported by means of the considered REM-based framework are further analyzed in section 4.11.

4.10.2 References

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4.11 Achievements JRA 1.3.3.A – REM-based interference management techniques and performance analysis

This section illustrates how the use of REMs, according to the general architecture described in the previous section, can lead to the definition of enhanced techniques for reducing interference in HetNets. This is done through some examples associated to different eICIC categories. To have a general and harmonized view, Table 4-2 identifies the categories of relevant REM parameters for each technique explained in the next subsections.

Table 4-2: Categorization of the parameters in the Local/global REM databases and how they are used by the different strategies

Category of parameters		Autonomous femtocell power adjustment	Macrocell-assisted power adjustment	Gibbs sampler based Frequency optimization	Wi-Fi offloading
Local REM	Locations of nodes	HeNB, UE locations	UE locations		AP location, UE location
	Radio related measurements	Propagation losses between network elements	Macro and HeNB UEs quality indicators, signal strength of victim MUEs, HUEs in outage	Propagation losses between users and cells	Received power level from APs and cells
	Transmit power		Transmit power per RB in each HeNB	Transmit power of each cell in each sub-band	Transmit power of the different nodes
	List of neighbour cells		Set of interfering HeNBs for each macro UE victim	Set of interfering cells for each cell	Set of neighbour APs
Global REM	QoS metrics	SINR target	SINR target		
	Locations of nodes	eNB locations			eNB locations
	Wi-Fi related information				Occupancy of the Wi-Fi channels, utilization level of IP connections, type of AP (fee-based access or free-based access, public or private)

4.11.1 Power control techniques

These techniques consist in adjusting the transmitted power to reduce the interference generated to victim users. Many of the proposed approaches in the literature reduce the power of small cells to limit the interference on the victim Macrocell User Equipments (MUE) usually at the expense of service degradation for HeNB Users (HUE). They are usually based on measurements performed locally by the terminals and/or cells, like in [1] where the received power from the strongest co-channel macrocell received by the HeNB is used to adjust the HeNB power. The use of REM can enhance the performance of these techniques by considering not only information related to Channel State Information (CSI) feedback from a UE to its serving eNB, but also information obtained by other means, e.g. from specific MCDs that fed the REM SA with measurements which in turn can be post-processed by the REM Manager unit. In the following, two examples of REM-based power adjustment strategies are presented.

4.11.1.1 Autonomous small cell power adjustment

One of the most challenging interference scenarios in two-tier networks is the interference caused by a HeNB to a nearby co-channel macrocell user [2]. The use of a REM in order to enhance the effectiveness of a baseline HeNB power control mechanism of [2] was proposed in [3]. The REM Manager may reside in either the HeNB or in the HeNB GW, and the HeNB uses the stored information autonomously, without a centralized control. The power control mechanism is a three step procedure. First the HeNB accesses the REM to get the radio propagation characteristics of the surrounding area and locate the position of the other neighbouring MUEs, HeNBs and eNBs. After detecting the presence of a neighbouring victim co-channel MUE, the HeNB adjusts its transmission power aiming to maintain a predefined Signal to Interference and Noise Ratio (SINR) target for the MUE by using the REM-stored context information. In case the SINR target cannot be met, the HeNB transmits at a predefined minimum power.

The related REM context information is listed in Table 4-2. The Global REM information includes the operator's network parameters, the users' SINR targets and the network's eNB locations. This type of information is usually stable for a long period of time, thus it can be easily accessed by a Local REM Manager at long time intervals by the use of X2 interface in a distributed architecture, and the S1 interface in a centralized architecture (see Figure 4-17). The Local REM related information is the HeNB and the victim MUE locations, and the radio propagation characteristics of the specific environment. It is worth mentioning that while the location of eNBs is known in advance, sometimes the HeNB location needs to be estimated since its exact location with respect to the interfering eNBs and MUE may be unknown (such as in the case of user's operated HeNB placed randomly inside a house). The added value of the REM-based algorithm with respect to the baseline of [2] is that it uses the stored information to estimate the channel gains between all the relevant network elements (HeNB, MUE, and its associated eNB) and then adjust the HeNB power accordingly. Since there is not a direct (feedback based) way for the HeNB to calculate the channel gain between the HeNB and the MUE, or between the MUE and the associated eNB, the REM Manager uses the stored radio environmental characteristics of the considered area plus the location of the network elements to estimate it. Instead, in the baseline case of [2], since the MUE location and the propagation environment are not known in advance at the HeNB, some fixed assumptions are made for these channel gains based on simulation studies and field measurements.

In [3] the benefit of using the REM-based HeNB power adjustment algorithm to protect a nearby co-channel macro user was presented. It was shown that the use of enhanced information can significantly reduce the MUE outage (i.e. the probability of being below the SINR target), with respect to the case where no such information was available. Figure 4-18 presents an illustrative example of the average MUE outage in a specific scenario with a transmitting co-channel HeNB in close proximity to a MUE (up to 50m). The REM-based algorithm is compared with the baseline one for various distances between the eNB and the MUE, for a fixed MUE SINR target of 3dB. The simulation scenario and parameters are based on the OFDMA Interference Scenario Evaluation Methodology for LTE femtocells [2] for the suburban case. The main conclusion from this study is that the REM-based approach can provide more benefits in the MUE protection when the macro-cell signal is stronger (small MUE/HeNB – eNB distance), than in the case of weak macro-cell signal (e.g. on the macrocell edge). In this case, the gain is restricted by the limited dynamic range of the HeNB transmit power, which prevents the transmit power to be below the minimum acceptable threshold, so similar results as with the baseline algorithm are obtained.

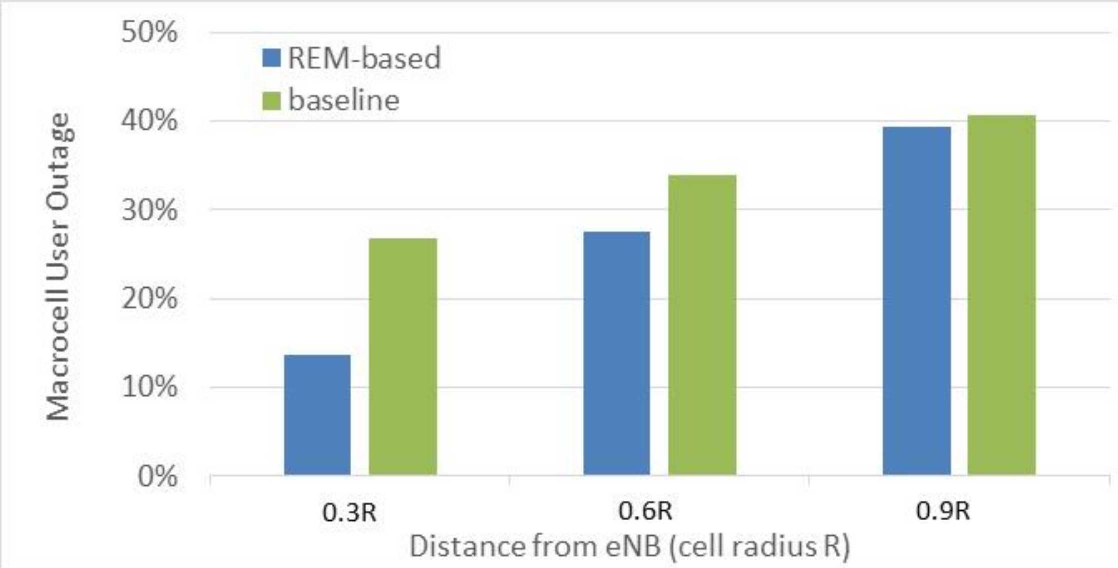

Figure 4-18: Average MUE outage for various distances between the eNB and the MUE (eNB radius R = 1km)

4.11.1.2 Macrocell-assisted small cell power adjustment

Macrocell-assisted power control methods are another alternative for cross-tier interference mitigation [4]. In such techniques, the eNB can support the small cells in their power adjustment through a dynamic power setting based on both global and local context information. Combining local and global REM information can enrich the decision policy and bring added value knowledge to the power allocation decision process.

The exchange of such environmental information through a cooperation process between the eNB and HeNB is part of the eICIC technique. Such cooperation can lead either to pure eNB power control decisions in which the centralized role of the eNB is fully exploited for taking optimized power adjustments to be applied by HeNBs, or to hybrid solutions where the eNB power control decision can be opportunistically adjusted by HeNBs based on local information.

A macrocell-assisted power adjustment strategy was proposed in [4] to improve the spectral efficiency of MUEs, while preserving an acceptable throughput to HUE users. To do so, the proposed mechanism makes use of several REM environmental parameters apart from the traditional SINR and RSS (Received Signal Strength) signals such as: the number of MUE victims and their set of interfering HeNBs, the interference score of each interfering HeNBs which reflects their participation in the global interference situation, and the number of affected HUEs, i.e. those who experience an outage situation (SINR below a minimum target) as a consequence of the last power adjustment cycle. As illustrated in Table 4-2, the context information including the CQI (Channel Quality Indicator), RSS, number and identity of victim MUEs, and HeNBs interference scores can be stored in the local eNB REM while the evolution of HUEs channel quality to detect any outage situation is captured by the local HeNB REM Manager. In this work, two versions of the adaptive power control mechanism were proposed. They differ in their selection strategy of the set of HeNBs to execute the power adjustment and the amount of power to reduce. Accordingly, the first version of the mechanism is more aware of HUEs performance degradation while the second version gives more priority to MUEs. The key feature of these solutions is that the power mitigation is based on power adjustment parameters that are dynamically tuned according to the interference weight of each HeNB on the global interference situation. To derive the HeNBs scores and adjust adequately their transmission power, it is suggested to allow the HeNB to periodically return the number of its HUEs in outage in case the requested power adjustment is causing significant degradation to a large number of its users. This information exchange can be realized through the X2 interface in the distributed architecture, or the S1 interface in the centralized architecture (Figure 4-17).

To emphasize the benefits of the REM-based approach in the macrocell-assisted power adjustment schemes, Figure 4-19 illustrates some performance results achieved by the proposal in [4]. The simulated scenario considers the deployment of 30 HeNBs in the coverage of one macrocell. Each HeNB is placed in a building and serves a maximum of 4 closed subscriber group users which move at a low speed compared to the outdoor users (3km/h vs. 30km/h). The REM-based approach with its two versions (noted v1 and v2 in Figure 4-19) is compared to a baseline solution where no REM-based power control is applied. Figure 4-19 illustrates the gain in MUEs throughput for CBR (Constant Bit Rate) flows as a function of the number of MUEs. A maximum gain of 18% is observed, while the throughput degradation of HUEs is limited to a maximum of 7%. All the obtained results in [4] showed the effectiveness of the proposed strategies which provide a good trade-off between MUEs and HUEs throughput under users mobility and service differentiation assumptions. The main conclusions that can be drawn here is that, regardless of the service classes, the REM-based power adjustment strategies fit perfectly the dense and mobile scenarios of urban areas and that the REM concept helps in capturing essential environmental information for the optimization approach.

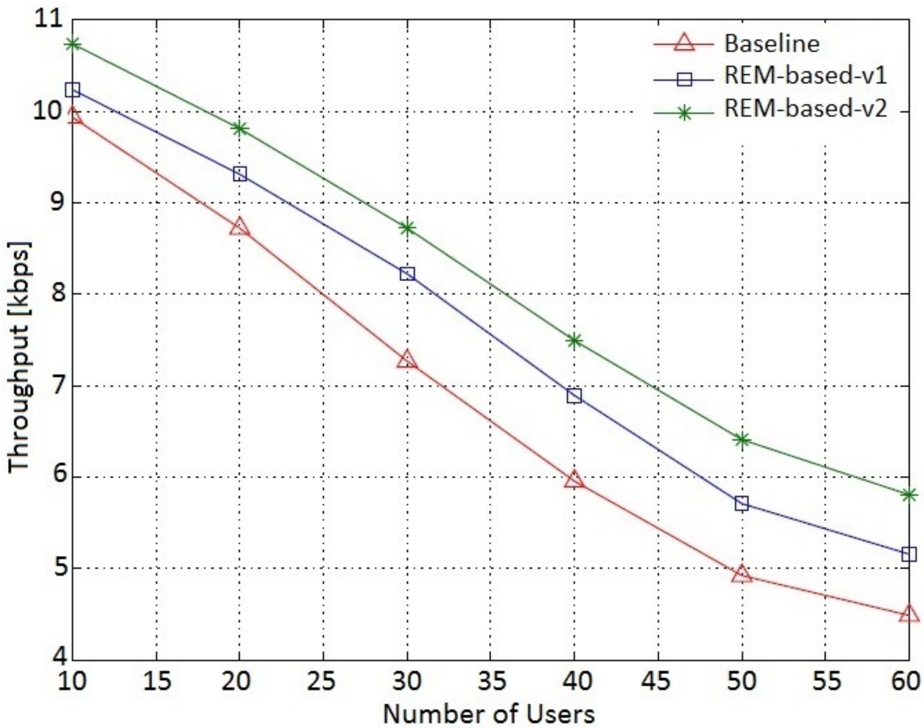

Figure 4-19: Throughput gain for macrocell users for CBR flows

4.11.2 Frequency domain techniques

In this category, different frequency resources are assigned to the users in the cells that can potentially interfere. One example is the Fractional Frequency Reuse (FFR) [5]. It consists in splitting the total band in different sub-bands that are allocated to the users located close or far away from the cell denoted as inner and outer users, respectively. The sub-bands of inner users can be fully reused in all neighbour cells, since these users receive less interference, while the sub-bands of the outer users, which receive more interference, are allocated following a reuse pattern between different cells. While the concept was originally applied for macrocells, it can be extended to HetNets with both macro and small cells.

The availability of REM information can play a key role in the optimisation process to decide the allocation of sub-bands. As an illustrative example, an extension of the Gibbs sampler based technique proposed in [6] for a macrocellular scenario is considered in the following for a HetNet. It targets the minimisation of the total intercell interference through the proper assignment of sub-bands to the inner and outer parts of the macrocells and to the small cells. This is done in a distributed fashion where each cell intends to minimise a local energy function that includes the interference seen by its users and the interference generated to the users in neighbour cells. To achieve this, at random instants defined by an exponential timer each cell modifies its own state (i.e. the used sub-bands) following a Gibbs-Boltzmann probability distribution in which low energy states are selected with higher probability. This is done iteratively so that the system progressively reduces the total interference (see [6] for further details of the algorithm).

To compute the local energy associated to each possible state, a given cell x needs to know the sub-bands currently used by its neighbour cells, their transmit powers, the propagation losses from each user in cell x to each neighbour cell and the propagation losses from cell x to the users in the neighbour cells. As listed in Table 4-2, this information can be retrieved by cell x from its local REM and the local REMs of its neighbour cells.

As an illustrative result, Figure 4-20 presents the increase in downlink average capacity per user achieved by the REM-based technique with respect to a reference scheme in a scenario with 12 macrocells and 8 small cells considering 4 sub-bands $\{f_0,f_1,f_2,f_3\}$. The reference scheme assumes that macrocells follow a classical FFR (with f_0 reused in all the inner parts and $\{f_1,f_2,f_3\}$ allocated to outer parts following a 3-reuse pattern) and that the sub-band allocated to a small cell is randomly selected among those not used by the closest macrocell. Each macrocell serves 10 users and each small cell 4 users. They are uniformly distributed in a radius 500m around the macrocell and 100m around the small cell, respectively. Small cells transmit 20 dBm and macrocells 43 dBm for the outer users while for inner users the power depends on the inner cell radius (i.e. the maximum distance at which inner cells can be located). In particular, two different values of the macrocell inner cell radius R_{in}, namely 200m and 350m, are considered, corresponding to transmit powers of the inner part 28dBm and 37 dBm, respectively. Propagation models are those from [6]. Capacity per user is evaluated by applying the Shannon bound to the SINR seen by each user.

Results in Figure 4-20 assume that the values of propagation losses stored in the REM are subject to random errors uniformly distributed in the range $[-\varepsilon,\varepsilon]$ that will impact on the local energy computations made by the Gibbs sampler. It can be observed that for the ideal case without errors (ε=0dB) in which the REM information matches the real propagation losses, the Gibbs sampler technique achieves very significant capacity gains between 30% and 55% for the small cell users, depending on the inner cell radius, with negligible impact on the capacity of macrocell users. As REM error ε increases, the capacity improvements are progressively reduced, although still keeping significant values, which reveals robustness in front of errors in the REM information.

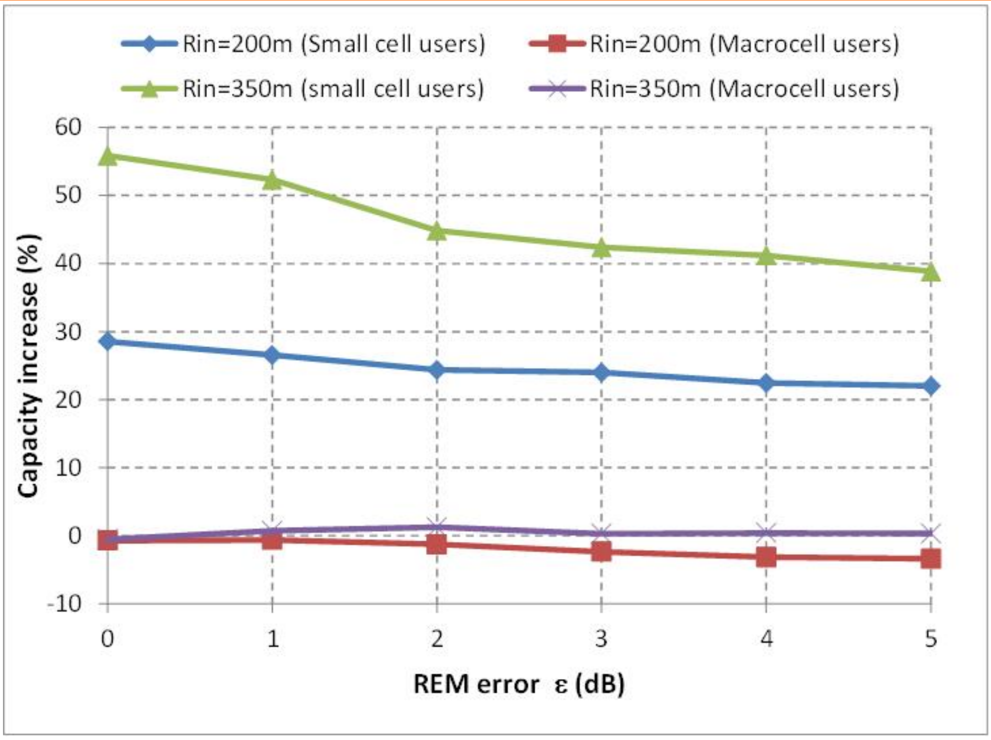

Figure 4-20: Capacity increase achieved by the REM-based Gibbs sampler optimisation mechanism for different values of the REM information error ε.

4.11.3 Optimization for data offloading

Efficient data offloading from the cellular network via the Wi-Fi network (or, in general, via other non-3GPP networks, although the focus of this work is on Wi-Fi networks) allows decreasing the HeNB/eNB load and, consequently, it can simplify the interference management applied by the mobile operator. Focusing on networks' integration, several aspects have to be considered: first, Wi-Fi access network is said to be interference limited; second, authentication can be required; third, fast internet connection has to be guaranteed; fourth, Wi-Fi access can be free or a fee may be required. These aspects of deeper integration between 3GPP and Wi-Fi networks are considered in the investigation on ANDSF and Hotspot 2.0 concepts. In that context the REMs can be considered as a technical enabler for efficient coexistence of cellular and Wi-Fi networks.

Referring to the network architecture presented in Figure 4-17, the global REM could contain information about the detailed location of potentially available Wi-Fi access networks including their ownership (e.g. private or public, fee-based access or free access, with or without authorisation, name of the owner, etc.). Moreover, the quality of the IP addressing options and the parameters of the available backhauling options for each Wi-Fi access network could be stored in the global REM. In turn, the local REM can store the information about the number of users currently served by the given Wi-Fi access points for each Wi-Fi channel (channel utilization status), users' location and transmit power, and the list of IP addresses, IMSI (International Mobile Subscriber Identity) numbers or other unique identifiers of the connected cellular users. By using this data the cellular network may allow the UE to connect to the Wi-Fi for data offloading. Moreover, by having knowledge of the IP addresses/IMSI numbers/identifiers, the offloaded traffic can be delivered to the end-users without entering the core network. Furthermore, as global REMs will have information about the neighbour lists of particular (maybe selected) Wi-Fi access points, the local REMs can contain detailed information about the closest neighbouring base stations / access points in order to allow handover between Wi-Fi and 3GPP networks.

Although efficient traffic offloading seems to be a very attractive solution for mobile network operator, from the interference management point of view it is just a technique that leads to the reduction of the overall traffic. Thus let us focus on how much of the traffic can be shifted to the Wi-Fi network without violating the quality of service. In [2][7], a dual-strip model of an office building with two floors has been considered, where the local (home) users can connect either via the cellular (either LTE macro or femtocell base station) or Wi-Fi network, while the users outside the building have to be served by the macro base station. The users can generate two types of traffic, voice (managed only by the cellular network) or data (that can be offloaded to the Wi-Fi network). Assuming that the REM has perfect knowledge on current Wi-Fi channel utilization, Wi-Fi access point and femtocell base station location, it has been shown that up to 30% of total traffic can be shifted to Wi-Fi network [7]. Of course, numerous other additional parameters than those mentioned above could be considered resulting in even higher modification of the percentage of offloaded traffic (in both directions). Therefore the non-3GPP traffic offloading creates high potential for traffic reduction and in consequence for easier interference management.

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4.12 Achievements JRA 1.3.3.A – Neighborhood cooperation algorithms for deciding TVWS spectrum assignment to small cells

Small cells (pico- and femtocells) in cellular networks are envisioned as a method of traffic offloading in densely populated areas. They are supposed to cover areas up to ~200 m (picocells) or in the order of ~10 m (femtocells), and therefore transmission power requirements are also moderate or low. Small cells can share frequency channels with macro cells, however in such a case, interference between small cells and a macrocell is an issue. Uncoordinated spectrum sharing between small cells may cause interference between them, what further degrades the benefit of small cells deployment. TV White Spaces (TVWS) defined as unused digital television (DTV) spectrum, interleaved in frequency and space, provide an opportunity for such a deployment due to the fact that small cells require low power.

Different works have recognized recently the potentials of applying spectrum sharing in TVWS to small cell scenarios. In [1], feasibility of utilizing TVWS spectrum for LTE TDD is discussed. The particularization to small cell scenarios is identified as a relevant use case to enhance the capacity while avoiding co-channel interference between adjacent small cells and between a macrocell and a small cell. In [2], it is concluded that the use of TVWS as a microcellular capacity booster in limited local areas is a plausible approach. It is found in [3], that, due to the high interference from TV towers, it is difficult to find channels that allow for good performance of cellular networks at the cell edge, while the inner part of the cell can obtain more benefits from TVWS. It is concluded that TVWSs are primarily suitable for traffic offloading and spotty coverage. In [4], the deployment of a cellular network in TVWS is analyzed, deriving a methodology to maximize the downlink capacity at the cell edge using a heuristic power allocation algorithm. It is concluded that only through dense cellular networks (i.e. small cell sizes) it is possible to efficiently exploit the secondary spectrum. The operation of a spectrum broker that assigns TVWS bands is presented in [5] considering the problem of matching multiple-bids to buy, and spectrum portfolio (offered by a spectrum broker). In turn, in [6] an auction approach for using TVWS with LTE and LTE-A is proposed. Resource allocation is modeled as a combinatorial auction with heterogeneous objects and profit maximization allocation rule. In [7] the use of TVWS is proposed to deal with the interference suffered by LTE macrocell users from nearby femtocells. The proposed approach is based on sensing of the interfering femtocells.

Based on the above, it is observed that many works have identified that the use of TVWS is seen as particularly relevant for extending the capacity of LTE and LTE-A networks with small cell scenarios. This activity intends to contribute to this problem by proposing neighborhood cooperation algorithm for assigning TVWS to small cells. It is based on a *first-come, first-served* principle. We focus on Region 1 spectrum, where the TVWSs lay between 470-790 MHz.

4.12.1 Spectrum broker operation for small cells with neighborhood cooperation

The emerging consensus for protection of the DTV incumbents is the geolocation database-controlled access by the secondary systems. These databases are supposed to contain: the area coordinates, the DTV channels available in this area and a maximum allowable transmission power for a specific radio transmitter with a predefined spectrum mask. The geolocation spectrum database has also been developed for Munich, Germany within the European project COGEU [8]. The methodology of the transmit power limit calculation in TVWS is described in [9]. The considered area of 60-by-60 km is divided to pixel areas of 200-by-200 m. For each pixel the maximum allowable transmission power is calculated in channels 40-60 (622-790 MHz) assuming fixed or mobile reception of the DVB-T that needs to be protected.

The spectrum broker is an entity managing and coordinating TVWS bands allocation to secondary users. Such a broker is responsible for planning, packaging the spectrum for secondary disposal, and resolving interference caused by its customers to the primary DTV systems or between themselves [5].

For the small cells (e.g. femtocells) it is envisioned that the base stations will be installed by the users themselves without any coordination, what may cause inefficient use of resources. One envisioned option is to direct the subscribers to the spectrum broker, as the coordinating entity. However, given the variety of the DTV channels availability at different locations and diverse power constraints, the variety of locations and bandwidth requirements, dependencies and interference constraints, it is a complicated task. Moreover, this optimization has to be performed every time a new femtocell is installed, what may be very dynamic. Thus, reassignments of resources may cause frequent connectivity problems in the given area. The other option for dynamic resource allocation to small cells is the assignment based on *first-come, first-served* rule. To this end, a new customer should go to the broker to access the geolocation database, and the local repository of DTV channels already in use. Before assigning a particular DTV channel, the broker has to make sure that there is no cell using the same channel at a distance at which interference from this channel can be observed. Because the frequency assignments cannot be optimized over all TVWS as new customers apply to the broker, there should be also some mechanism to update the TVWS channels assignment for better spectrum usage and efficient energy management.

Figure 4-21 presents the general high-level framework considered in this activity for the assignment of TVWS to small cells. Based on the information from the geolocation database, the broker will have the spectrum portions, each one with a central frequency f_i, bandwidth B_i, power limitations $P_{\mathrm{Tmax}\ i}$, and locations L_i, where each portion can be used. This list will be dynamically updated by the spectrum broker taking into consideration previous assignments. When the operator, or more specifically the OAM (Operations, Administration and Maintenance) functionality, identifies that additional spectrum is required in a certain area for a small cell, it will request this shared spectrum to the broker. The request made at the nth moment should include the requirements in terms of requested bandwidth $B_{\mathrm{R}n}$, transmit power $P_{\mathrm{TR}n}$ and location $L_{\mathrm{R}n}$ where spectrum is needed. Then, the spectrum broker will provide an assignment of the spectrum portions.

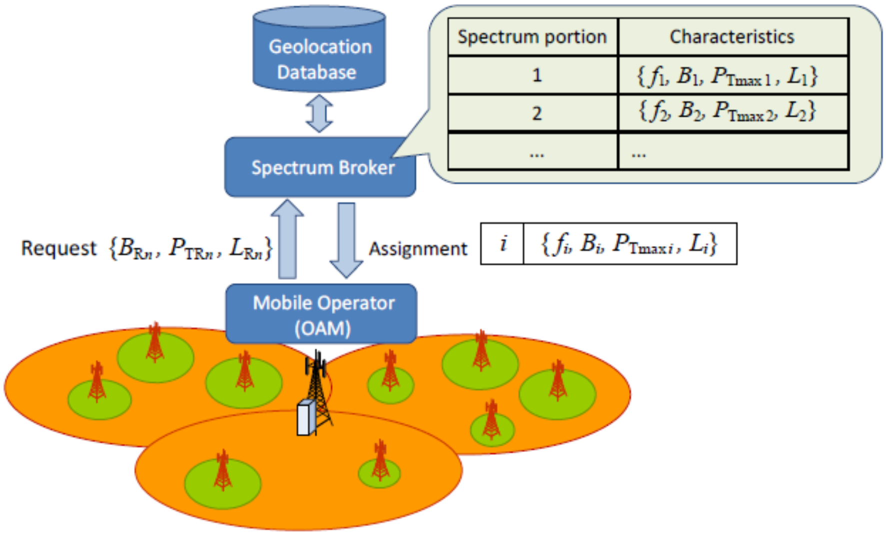
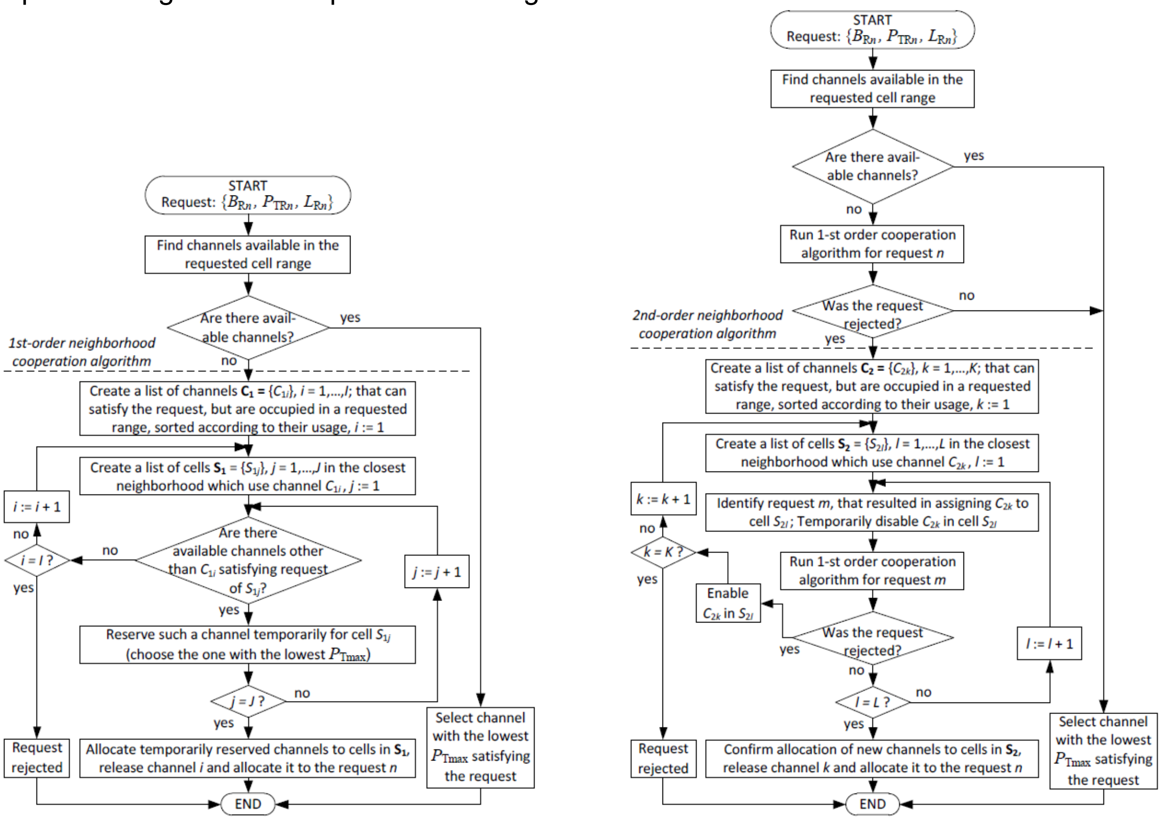


Figure 4-21: Framework for TVWS assignment to small cells

Based on the described framework, the task of the OAM at the operator's network is to identify additional spectrum needs for specific geographical areas (i.e. deployed cells) that can be solved by allocating TVWS spectrum. As for the requested bandwidth, if considering LTE or LTE-A as a reference system, it will depend on the carrier bandwidth that belongs to the set {1.4, 3, 5, 10, 15, 20} MHz [10] and on the number of requested carriers. As for the transmit power, focusing on the downlink, it will be given by the envisaged coverage area, while if considering the uplink the required power will be given by the terminal. Being this study mainly focused on the operation of the spectrum broker, spectrum requirements will be considered only for the particular case that a small cell requires just one DTV channel in TVWSs.

If we consider the *first-come, first-served* principle, an easy algorithm for the TVWS spectrum assignment to a new small-cell request would scan the available DTV channels in a given location, and assign a first available channel or an available channel with the lowest allowable transmit power. By this *availability* we mean that the allowable transmit power in this channel is higher or equal to the requested power. In such a case, a request to which there are no available channels would be rejected. Let us consider an algorithm for the TVWS spectrum assignment for small cells, which does not reject requests but employs neighborhood cooperation to rearrange the assignments to satisfy such requests. It is presented in Figure 4-22a. The algorithm starts with checking the database to see, if there are DTV channels in the new small-cell location with the power limit equal or higher than the requested value for the assumed coverage (checking this availability includes co-channel interference analysis in the neighborhood area). If there are available channels the one with the lowest power limit satisfying the TX power requirements for the new cell is chosen. If there is no available channel, the algorithm checks if there are channels occupied in this area, which can be released by allocating different channels to the existing cells. If so, the channels are rescheduled in this area and the released channel is assigned to a new cell. The allowable transmit power limit in this channel is decreased in the surrounding area to limit the co-channel interference.

The last step in the above described algorithm is crucial for efficient spectrum allocation in the considered scenario. The goal is to use as little resources as possible to satisfy the customers' requirements. The algorithm handles the neighborhood cooperation, where by *neighborhood* only the adjacent neighboring cells are meant. In the following, this kind of neighborhood will be called *closest neighborhood* and the cooperation among cells in this closest neighborhood will be called *1st order neighborhood cooperation*. Extension of this notion to more distant cells will be called *2nd order neighborhood*. In such a case, if there is no possibility of bartering the channels with the adjacent cells, each of these cells are examined on the possibility to exchange channels within its own closest neighborhood, and to release the channel that can be used by the new arriving small-cell request. This option is characterized by increased complexity. Both, the 1st-order and the 2nd-order neighborhood cooperation algorithms are presented in Figure 4-22.



(a) (b)

Figure 4-22: The 1st-order (a) and the 2nd-order (b) neighborhood cooperation algorithms

4.12.2 Numerical results

The above described algorithms have been examined through computer simulations in two scenarios: Munich city center of 1.8-by-1.8 km using TVWS geolocation database [8], and a hypothetical reference environment with availability of TVWS generated randomly in all pixel-areas. In this reference scenario, the degree of freedom in DTV channel assignment is very high and should provide upper-bound results in TVWS utilization by small cells. The granularity of Munich geolocation database has been increased by introducing pixels of 10-by-10 m. The same has been assumed for the hypothetical environment mentioned above, thus, introducing correlation of TVWS availability in such a region.

We have examined two kinds of random small-cells requested-power Rayleigh distributions which relate to the requested coverage and impacts the number of available channels. This distribution has been truncated by maximum requested power values stated for femto and picocells. For femtocells the average and the maximum EIRP of 4 dBm and 17 dBm have been assumed respectively. For pico cells the average and the maximum EIRP has been set to 15 dBm and 21 dBm respectively. The associated coverage of the cells was 3-30 m for femto-, and 30-180 m for picocells. The socalled *safety belt* around each small cell area has been calculated for each cell to meet the requirement of the receiver protection ratio equal to -20 dB. The used propagation model was Extended Hata model for indoor environment [11].

The following four algorithms of DTV channels assignment to small cells based on *first come, first served* have been considered: (i) assignment of the first available DTV channel in a given location, (ii) assignment of the channel with the lowest transmit power limit, higher or equal to the requested power, (iii) allocation based on the 1st-order neighborhood cooperation algorithm from Figure 4-22a, (iv) allocation based on the 2nd-order neighborhood cooperation (Figure 4-22b).

In Figure 4-23, the satisfied requests rate (the ratio between the number of satisfied requests and all occurring requests) is presented for our four allocation rules. This satisfied requests rate translates to the efficiency of TVWS spectrum resources usage. In Figure 4-24, the average transmit power levels per channel allocation are presented. This average power level is an indicator of how well the available power is used. Note that neighborhood cooperation can improve the performance in terms of the efficiency of TVWS spectrum resources usage and the available power-resources usage with respect to simple channel-allocation methods for both types of small cells dominating the requests: femto- and picocells.

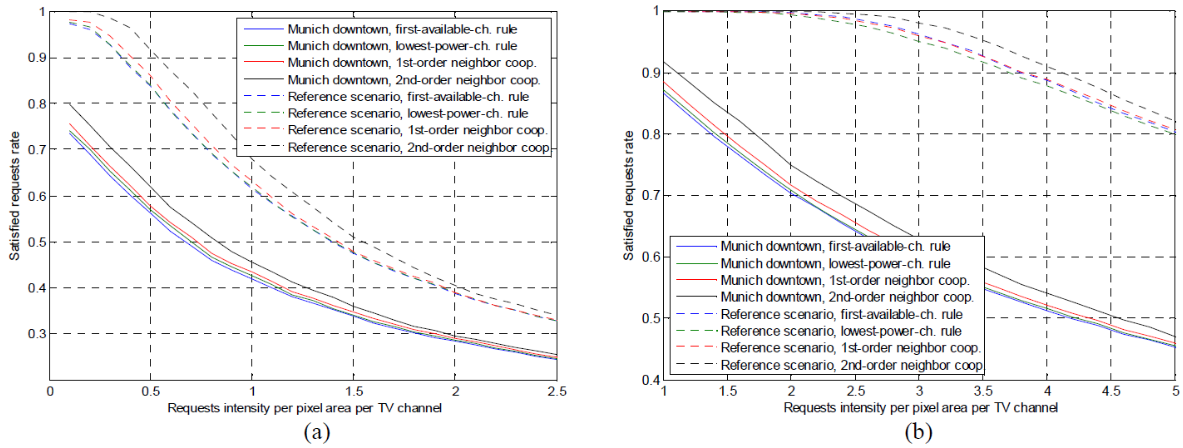
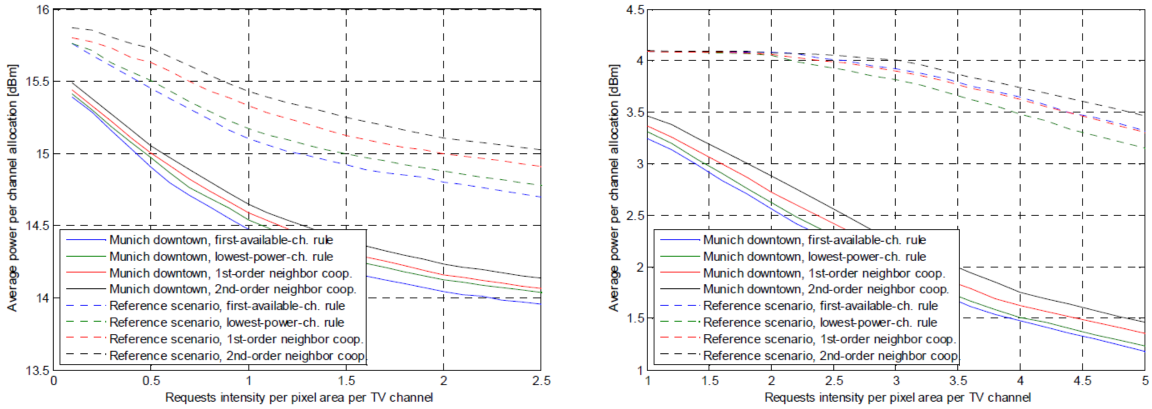


Figure 4-23: Satisfied requests rate in case of (a) 6 DTV channels available for the picocells dominating requests and (b) 13 DTV channels for the femtocells dominating requests.



(a) (b)

Figure 4-24: Average power per channel allocation in case of (a) 6 DTV channels available for the picocells dominating requests and (b) 13 DTV channels for the femtocells dominating requests.

4.12.3 References

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4.13 Achievements JRA 1.3.3.A – Maximum transmit powers for indoor small cells using TVWS

4.13.1 Description

This section presents some initial results concerning the maximum transmit power that can be allowed for a small cell deployed in an indoor scenario, in order not to interfere with TV receivers, by making use of the measurements that have been obtained in JRA #G of WP2.1.

For that purpose, an indoor REM database is considered containing a 3D characterisation of the radioelectrical propagation of the DVB-T signals inside the building. The following information is assumed to be stored:

- Semi-static information: This corresponds to information elements that are not supposed to vary during secondary system operation, so that they can be acquired at some point of time and be valid for a long period of time as long as regulatory conditions do not change (i.e. no new DVB-T licenses are assigned) nor new DVB-T transmitters appear. In particular, the following elements are considered:
  - $P_r(\theta,N)$: Received power level of the DVB-T signal at each position $\theta=(x,y,z)$ inside the building for each TV channel N.
  - $PR(i)$: Required Protection Ratio (PR) to ensure DVB-T reception in channel N when the secondary transmitter is working at channel $N+i$. Note that the case $i=0$ corresponds to the co-channel protection ratio while the case $i>0$ corresponds to the i-th adjacent channel protection ratio.
  - $P_{r,min}$: Minimum received power level to ensure successful DVB-T reception.
  - $L(d)$: Indoor propagation model to characterise the losses between any two points of the building as a function of the distance d and the building characteristics (e.g. number of floors, etc.).
- Dynamic information: This corresponds to information that needs to be updated dynamically depending on the operation of the secondary system. The following information is considered:
  - $P_{Tmax}(\theta,N)$: Maximum allowed transmit power for a secondary transmitter located at position $\theta=(x,y,z)$ and operating on TV channel N. This maximum power level will depend on the PR requirements of the DVB-T receivers and on the number and positions of the currently active secondary transmitters inside the building, in order to ensure that the aggregated interference that they generate is below the acceptable limits established by the PR. Correspondingly, this information needs to be updated every time that a new small cell is activated or deactivated in the considered building.

In order to compute the maximum allowed transmit power this work will focus on the worst case scenario in which the positions of the DVB-T receivers are unknown (e.g. in case of USB-stick DVB-T receivers connected to laptops that can be in any part of the building). However, in indoor scenarios other situations could also be considered in which e.g. the positions of the at least static DVB-T receivers could be registered in the database as well, or in which the only DVB-T reception point is the antenna at the rooftop.

Assuming there is no other secondary transmitter in the building, the maximum allowed transmit power at point $\theta=(x,y,z)$ for a general channel $N+i$ needs to fulfil the following condition for any point θ' where a DVB-T receiver could be located:

$$\frac{P_r(\theta',N)}{\dfrac{P_{T\max}(\theta,N+i)}{L(\theta,\theta')}} \geq PR(i) \tag{4.13.1}$$

where $L(\theta,\theta')$ denotes the propagation losses between the point θ where the secondary transmitter is located and the point θ' where the potential DVB-T receiver could be located. Based on this relationship the following distinction is done:

1) Co-channel secondary transmission (i=0)

In this case, it will be assumed that no secondary transmission is allowed at point θ if DVB-T reception is possible at this point (i.e. if $P_r(\theta,N)\geq P_{r,min}$). Though this condition would not be strictly necessary in theory as long as the protection ratio $PR(0)$ constraint is ensured when determining P_{Tmax}, in practice this would lead to very small values of transmit power that would actually prevent the secondary transmission. For this reason, we restrict secondary transmission to the points θ where DVB-T reception is not possible. In this case, the maximum transmit power is obtained from the most restrictive of the points θ' where DVB-T reception is possible. Then, from (4.13.1) it is obtained that:

$$P_{T\max}(\theta,N) = \begin{cases} 0 & \text{if } P_r(\theta,N) \geq P_{r\min} \\ \min\limits_{\theta' \text{ s.t. } P_r(\theta',N) \geq P_{r\min}} \left[\dfrac{P_r(\theta',N) \cdot L(\theta,\theta')}{PR(0)} \right] & \text{if } P_r(\theta,N) < P_{r\min} \end{cases} \quad (4.13.2)$$

2) Adjacent channel secondary transmission (i>0):

The main difference with the previous case is that now, since *PR*(*i*) values are much lower than in the co-channel case, transmission in the adjacent channel *N+i* can be considered even at a point where the DVB-T reception in channel *N* is possible. Then, from (4.13.1) the maximum transmit power is given by:

$$P_{T\max}(\theta,N+i) = \min_{\theta' \text{ s.t. } P_r(\theta',N) \geq P_{r\min}} \left[\frac{P_r(\theta',N) \cdot L(\theta,\theta')}{PR(i)} \right] \quad (4.13.3)$$

For the case $\theta=\theta'$ in which the secondary transmitter and the DVB-T receiver are located in the same position, it is assumed that in practice there will be always a minimum physical separation between the secondary transmitter and the DVB-T receiver [1], so $L(\theta',\theta')$ equals a minimum propagation loss L_{min} related with this physical separation.

The above computations can be easily extended to the case in which there already exist other secondary transmitters in the building, so that it has to be ensured that the total interference generated by all the transmitters does not exceed at a given position the maximum allowed interference in accordance with the required protection ratio. In deliverable D21.3 of WP2.1 further details about this computation in the case that another secondary transmitter exists can be found. Similarly, in that deliverable, details about the measurement set-up and the measurements that have been used to build the indoor REM database are also given. Specifically, measurements have been done in a four-level building consisting of basement, ground floor, first and second floors.

To assess the maximum allowed transmit power levels for a small cell deployed in an indoor position, let consider first the possibility of having co-channel transmission in channel N=61, which is one of the occupied DTV channels considered in the measurements. Given that the considered building has direct line-of-sight and short distance with the TV tower transmitter, DVB-T reception is possible in most of the points inside the building (assuming a minimum required power of $P_{r,min}$=-80.5 dBm), which prevents from the possibility of doing co-channel transmission in most of the cases. The only exceptions are a few points located at the basement, which is located below the street level. These points represent only 7.23% of the points in the building. Table 4-3 presents the P_{Tmax} statistics for these points according to (4.13.2) for two types of DVB-T receivers considered in the study, i.e. a USB stick and a TV Set with an Integrated Digital TV tuner denoted as IDTV. The PR requirements for these TV receivers are taken from [2]. It is observed in Table 4-3 that the maximum allowed transmit power takes actually very small values that would limit the coverage of the secondary transmitter to very few meters. In this respect it is not envisaged that these values could allow for the deployment of a small cell to provide satisfactory coverage in different parts of the building.

Table 4-3: P_{Tmax} for co-channel transmission in N=61

P_{Tmax}	USB Stick	IDTV
Min	-51.95 dBm	-50.95 dBm
Avg	-46.59 dBm	-45.59 dBm
Max	-39.50 dBm	-38.50 dBm

Concerning the secondary transmission in adjacent channels, Figure 4-25 plots the Cumulative Distribution Function (CDF) of the maximum allowed transmit power P_{Tmax}

according to (4.13.3) for the different points inside the building. Results are presented for both adjacent channels *N*+1 and *N*+2 and for both types of DVB-T receivers. As it can be observed, the allowed power levels are substantially higher than in the co-channel case, so it can be feasible the potential deployment of a small cell acting as a secondary transmitter. Specifically, when considering the USB-Stick DVB-T receiver, 90% of the points have a maximum allowed transmit power between −12 dBm and 9 dBm in the first adjacent channel, and between −10 dBm and 11 dBm in the second. Moreover, in half of the points the transmit power can be higher than −6 dBm in the first adjacent channel, which can be assumed a feasible level for successfully deploying an indoor small cell. For the IDTV receiver these values increase in around 2 dB.

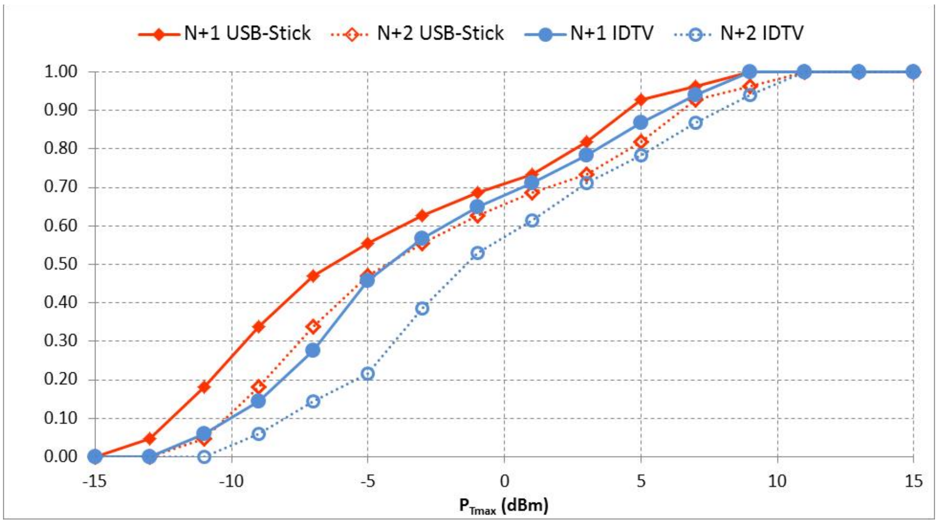

Figure 4-25: CDF of the maximum transmit power P_{Tmax} for first and second adjacent channels

Further measurements and computations, including the statistics of the maximum transmit power for different areas of the building and the computations when there is another secondary transmitter in the building can be found in deliverable D21.3 of WP2.1.

4.13.2 References

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4.14 Achievements JRA 1.3.3.A – Interference Coordination scheme for HetNets exploiting jointly the frequency, power and time dimensions

Conventional user-to-cell association methods based on measured received signal strength (RSS) or Signal to Noise and Interference (SINR) ratio (i.e. the UE connects to the cell with the highest RSS or SINR) [1] may be suboptimal in the case of HetNet deployments because of the lower transmit power of small cells, which reduces the number of users that can be connected to them and thus the traffic that is offloaded from the macrocells. To overcome this issue, a technique known as Cell Range Expansion (CRE) is introduced [2][3]. It consists in extending the small cells coverage footprint by adding a cell bias in the measured RSS or SINR. This comes at the cost of a major interference from the other cells particularly for those users in the expanded region that are connected to the small cell but receive higher power from the macrocell.

Therefore, in LTE-A, eICIC techniques [4] have been proposed to comply with the new requirements of the HetNets including CRE. Subframe alignment [5] is a Time-Domain eICIC scheme that divides the subframes in two types, Normal and Almost Blank Subframes (ABS). The purpose is that the cell that generates interference is not allowed to transmit user data during an ABS subframe giving the opportunity to the victim cell to transmit under reduced interference. In this way, by avoiding data transmission during ABS subframes in the macrocell, these subframes can be used by the small cell users in the expanded region, so that they will suffer from less interference. An ABS duty cycle calculation method is proposed in [6], where the authors also include a load balancing algorithm. The combination of the two schemes results in better use of resources and user throughputs. In [7], a distributed approach for synchronous ABS is presented where the authors exploit dynamic programming to determine the victim users and the optimal number of ABS.

In this way, CRE and the eICIC concepts have been proved to get significant improvements. However, the available resources are underutilized since the macro cell is not allowed to transmit data during the ABS subframes, which may lead to degradations in the achieved throughput. Therefore, strategies making use of ABS and CRE concepts need to be carefully devised according to the trade-off between interference reduction in the small cells and throughput degradation in the macro cells. Under this framework, in this section we propose a novel approach that allows a better exploitation of the system resources according to the specific small cell deployment and the current traffic load by jointly exploiting the frequency, power and time dimensions, which are usually addressed separately.

4.14.1 System model

The system used in this work is comprised by a set of $i = 1, \dots, M$ macrocells, and a set of $k = 1, \dots, S$ small cells. A set of users *U* are non-homogeneously distributed in the scenario, forming some hot spot areas with higher user density than other parts. The user-to-cell association is carried out according to the measured RSS with CRE being applied and with the cell bias denoted as $\Delta\ (dB)$. As a result, the set of users connected to the i^{th} macrocell is denoted as $U_{M,i}$ and the set of users connected to the k^{th} small cell is denoted as $U_{S,k}$. The users in the k^{th} small cell are further classified as the subset of CRE users ($U_{CRE,k}$), which are the users that belong to the extended region of the k^{th} small cell (i.e. users that are connected to the small cell but they receive a higher RSS from the macrocell) and the subset of normal users ($U_{N,k}$), which are the users connected to the k^{th} small cell and receive the higher RSS from the small cell. Note that $U_{CRE,k} \cup U_{N,k} = U_{S,k}$.

Communication in the downlink direction is assumed. The resource allocation follows the LTE specifications, where the frequency dimension is organized in a total of *numRB* Resource Blocks (RBs) of bandwidth B_{RB}=180 kHz and the time dimension in subframes of 1 ms organized in frames of 10ms. As such, the available RBs in a frame are numbered as *RB*(*f*,*t*) where *f*=1,...,*numRB*, and *t*=1,...,10. It is assumed that each cell carries out the scheduling in each frame to decide the allocation of the RBs to the users. The smallest allocation unit to a user is one RB in one subframe. ABS technique is applied with μ denoting the number of the ABS subframes per frame. Non-ABS subframes are denoted as Normal subframes.

The total propagation losses in the *RB(f,t)* for a user $u \in U$ with respect to the i^{th} macro and the k^{th} small cell are denoted as $L_{M,u,i,RB(f,t)}$ and $L_{S,u,k,RB(f,t)}$, respectively. They include the shadowing and the fast fading due to multipath.

4.14.2 Proposed solution

The key idea of the proposed solution is to improve the current trade-off between interference reduction in the small cells and throughput degradation in the macrocell due to the silent periods during ABS frames, based on jointly considering the frequency, power and time dimensions when deciding the allocation of users to RBs. In particular, the proposed approach assumes that a more efficient use of the resources can be achieved to increase the macrocell throughput if, instead of totally avoiding data transmission during the ABS subframes, smart mechanisms are applied that allow transmission in these subframes under special constraints to avoid generating an excess of interference to the small cells. Such conditions are expressed in terms of the allowed RBs in the frequency domain or the maximum allowed transmit power. In particular, considering the i^{th} macrocell and the small cells falling in the coverage area of this macrocell, the strategy makes the following distinction, as shown in Figure 4-26.

Case 1: Whenever the small cells are located at a high distance from the macrocell (i.e. the distance d_s between the macrocell site and the closest small cell site is above a certain threshold *Ths*), we take advantage of the fact that the small cell users suffer inherently less interference from the macro cell. As such, transmissions of the macrocell users on the ABS subframes could be allowed with the restriction of a lower transmit power. In order to do so, the macro cell is split in two parts, the outer and the inner. This is done by classifying as outer users the macrocell users with an average propagation loss (i.e. without including fast fading) to the macrocell above a certain threshold (L_{th}) and as inner users the macrocell users with average propagation loss below the threshold. The subset of outer users of the i^{th} macrocell is $U_{O,i}$, and the subset of inner users is $U_{I,i}$. The value of the L_{th} is set such that, according to the propagation model, the distance associated to L_{th} is lower than the distance d_s to the closest small cell.

In this way, the inner users are allowed to be allocated in the RBs of the μ ABS subframes with reduced power level, while outer users can only be allocated in the RBs of Normal subframes. Then, the transmit power per RB for the i^{th} macrocell will be $P_{TM,i,low}$ for the ABS subframes allocated to inner users and $P_{TM,i,high}$ for the Normal subframes allocated to either outer or inner users.

As for the resource allocation in the small cell, the CRE users are allocated only in ABS subframes and the normal users are allocated preferably in ABS subframes but they can also use normal subframes when there are not sufficient RBs in the ABS subframes. The transmit power per RB of the k^{th} small cell will be $P_{TS,k}$ in all the subframes allocated to small cell users. The abovementioned allocation criteria for both macro and small cell users in Case 1 are graphically summarized in Figure 4-26 (a).

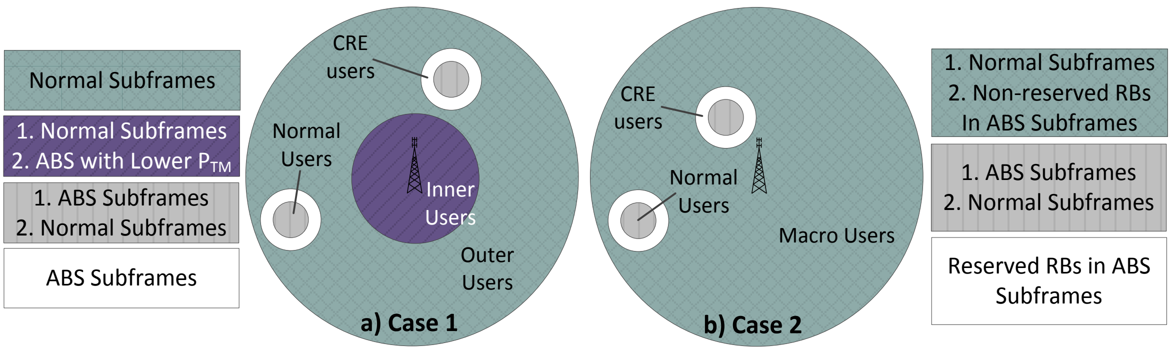

Figure 4-26: Allocation criteria for Case 1 (a), and Case 2 (b)

Case 2: If any of the small cells is located close to the macro cell, (i.e. the distance d_s between the macrocell and the closest small cell is below threshold *Ths*) the small cell users are more susceptible to the interference from the macro; therefore a simultaneous use of the ABS subframes is not possible even if the macrocell would transmit with lower power in these subframes. As such, an alternative strategy is applied where the splitting takes place in the frequency domain. We define a number of RBs $\varepsilon \le numRB$ as especially reserved RBs in each ABS subframe. These reserved RBs will not be used by the macrocell for data transmission. Instead, they will be mainly devoted for the CRE small cell users since they are those that are more sensitive to the macrocell interference. Then, the macrocell users will be allocated to either normal subframes or to the $(numRB - \varepsilon)$ non-reserved RBs in the ABS subframes. As such, we avoid having the macrocell completely silenced during an ABS subframe, increasing in this way the macro capacity. The key factor here is that the number ε of reserved RBs may be reconfigured depending on the amount of the CRE users. In particular, in this work we assume the following:

$$\varepsilon = \min\ ([\alpha \cdot numCRE], numRB) \qquad (4.14.1)$$

where α is a parameter of the algorithm, $numCRE$ is the total number of CRE users in the small cells within the coverage area of the i^{th} macrocell and [·] represents the rounding operation to the nearest integer value.

In this way, if there are few CRE users, we reduce the value of ε, while as the number of CRE users increases we approach the conventional ABS scenario where the macrocell cannot transmit in any of the RBs (i.e. $\varepsilon = numRB$). The CRE users of the small cells will be allocated only in the reserved RBs of the ABS subframes, while the normal users will be allocated preferably in the ABS subframes (both reserved and non-reserved), but they are allowed to utilize the Normal subframes if there are not sufficient RBs in the ABS subframes. The transmit power per RB of the i^{th} macrocell in this case will be $P_{TM,i,high}$ for all the subframes. In turn, the transmit power per RB of the k^{th} small cell will be $P_{TS,k}$. The abovementioned allocation criteria for both macro and small cell users in Case 2 are graphically summarized in Figure 4-26 (b).

The pseudo-code of the scheduling algorithms for allocating the different RBs to the users according to the abovementioned proposed strategy are presented in Figure 4-27 and Figure 4-28 for the macrocells and the small cells, respectively.

The scheduling follows the principles of the Proportional Fair (PF) algorithm [8] in order to prioritize the different users. In particular, for each user u (where $u \in U_{M,i}$ when doing the scheduling for the users in the i^{th} macrocell and $u \in U_{S,k}$ for the users in the k^{th} small cell) the following priority metric is defined associated with each $RB(f,t)$:

$$m_{u,RB(f,t)} = \frac{R_{u,RB(f,t)}}{W_u} \qquad (4.14.2)$$

$R_{u,RB}(f,t)$ is the achievable bit rate by the user in $RB(f,t)$ given by:

$$R_{u,RB(f,t)} = B_{RB} \log_2 \left(1 + \left(\frac{S}{N} \right)_{u,RB(f,t)} \right) \qquad (4.14.3)$$

where $(S/N)_{u,RB(f,t)}$ is the signal to noise and interference seen by the user in $RB(f,t)$. In turn, W_u is the bit rate experienced by the user averaged over a window of the last T_W frames, so it depends on the past allocation of RBs to this user. After each frame, W_u is updated taking into account the actual bit rate achieved by user u in its allocated RBs. In order to avoid allocating an RB with very low bit rate, a user u is only considered as candidate for the assignment of $RB(f,t)$ if $R_{u,RB}(f,t)$ is above a specific threshold $R_{b,min}$. In addition, the maximum number of RBs that can be allocated to a single user u in one frame is limited by the fact that the aggregation of the bit rates $R_{u,RB}(f,t)$ in the RBs allocated to this user should be below a maximum value $R_{b,max}$. This aggregated bit rates for a given user u is denoted as Σ_u in the pseudo-code, and is updated each time that an RB is allocated to this user u.

Scheduling Algorithm in the i-th macrocell for a frame

1: *compute $m_{u,RB}(f,t)$ for each user $u \in U_{M,i}$,for all RBs*
2: *initialize $\Sigma_u=0$ for each user $u \in U_{M,i}$*
3: ***for** each normal subframe t* *//Normal subframes*
4: ***for** (f=1;f<=numRB)*
5: *U_{aux}=set of users in $U_{M,i}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$*

$u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
allocate RB(f,t) to user u with* $P_{TM,i,High}$
$\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
end for
end for
for *each ABS subframe t* //ABS subframes
if *(ds<Ths)* // Case 1
for *(f=1;f<=numRB)*
U_{aux}=set of users in $U_{I,i}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
$u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
allocate RB(f,t) to user u with* $P_{TM,i,Low}$
$\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
end for
end if
else if *(ds>Ths)* // Case 2
for *(f=1;f<=numRB-* ε*)* //only non-reserved RBs
U_{aux}=set of users in $U_{M,i}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
$u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
allocate RB(f,t) to user u with* $P_{TM,i,High}$
$\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
end for
end else if
end for

Figure 4-27: Macrocell Scheduling Algorithm

Scheduling Algorithm in the k-th small cell for a frame

compute $m_{u,RB}(f,t)$ *for each user* $u \in U_{S,k}$ *,for all RBs*
initialize $\Sigma_u=0$ *for each user* $u \in U_{S,k}$
for *each ABS subframe t* // ABS subframes
if *(ds<Ths)* // Case 1
for *(f=1;f<=numRB)* //all the RBs
U_{aux}=set of users in $U_{CRE,k}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
if $U_{aux} = \varnothing$
U_{aux}=set of users in $U_{N,k}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
end if
$u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
allocate RB(f,t) to user u with* $P_{TS,k}$
$\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
end for
else if *(ds>Ths)* // Case 2
for*(f=1;f<=* ε*)* //reserved RBs
U_{aux}=set of users in $U_{CRE,k}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
if $U_{aux} = \varnothing$
U_{aux}=set of users in $U_{N,k}$ with $R_{u,RB(f,t)} > R_{b,min}$ and $\Sigma_u < R_{b,max}$
end if
$u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
allocate RB(f,t) to user u with* $P_{TS,k}$
$\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
end for
for*(f=1;f<=numRB-* ε*)* //non-reserved RBs
U_{aux}=set of users in $U_{N,k}$ with $R_{u,RB(f,t)} > R_{b,min}$ and $\Sigma_u < R_{b,max}$
$u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
allocate RB(f,t) to user u with* $P_{TS,k}$
$\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
end for

end else if
end for
***for** each normal subframe t* //*Normal subframes*
***for** (f=1;f<=numRB)*
U_{aux}=*set of users in* $U_{N,k}$ *with* $R_{u,RB(f,t)}>R_{b,min}$ *and* $\Sigma_u < R_{b,max}$
$u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
allocate RB(f,t) to user u with* $P_{TS,k}$
$\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
end for
end for

Figure 4-28: Small Cell Scheduling Algorithm

4.14.3 Simulation results

The evaluation of the performance of the proposed scheme has been carried out through simulations. The simulation scenario consists of one macrocell and two small cells. A set of 90 users are homogeneously distributed in the scenario. In addition, a number of users is distributed in form of a hotspot, as seen in Figure 4-29, where two different configurations of the positions of the small cells are considered. The number of users in the hotspot is varied in the simulations.

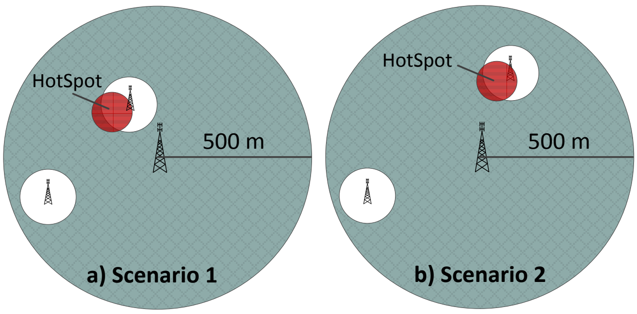

Figure 4-29: Simulation Scenarios

The different parameters of the algorithm are shown in Table 4-4. They have been set based on different simulations not shown here for the sake of brevity. Moreover, for case 2 the number of the reserved RBs ε is calculated according to (4.14.1) with $\alpha=2/\mu$. This value is obtained considering that each CRE user will require on average 2 RBs to transmit. The general model used for computing the total propagation losses with respect to the macrocells $L_{M,u,i,RB(f,t)}$ and the small cells $L_{S,u,k,RB(f,t)}$ is given by:

$$L(dB) = 128.1 + 37.6 \log d(km) + S - 10 \log F \qquad (4.14.4)$$

where d is the distance between user u and the cell site, S(dB) is the shadowing modelled as a Gaussian random variable with standard deviation σ = 6 dB, F is the fast fading due to multipath, modelled as an exponential random variable with average 1 assumed independent for each RB and frame.

In case 1 the threshold used for the classification of users into inner and outer is set to L_{th}=101.8 dB. This value corresponds to an inner cell radius of 200m according to the propagation model.

For the evaluation of the system performance we use the average capacity per user. This is computed by averaging over all the simulated frames the capacity C_u that a user u gets in each frame. C_u is computed by aggregating the bit rate in all the RBs allocated to the user u in this frame, that is:

$$C_u = \sum_{RB(f,t) \text{ allocated to user u}} B_{RB} \log_2 \left(1 + \left(\frac{S}{N} \right)_{u,RB(f,t)} \right) \tag{4.14.5}$$

where $(S/N)_{u,RB(f,t)}$ is the signal to noise and interference ratio experienced by user *u* in the *RB*(*f*,*t*).

Table 4-4: Simulation parameters

numRB	Number of RBs	25
μ	Number of ABS subframes	1 to 6
Δ	Cell Bias	3 dB
$P_{TM,i,high}$	Macro Transmit Power (high level)	29 dBm
$P_{TM,i,Low}$	Macro Transmit Power (reduced level)	11 dBm
$P_{TS,k}$	Small cell Transmit Power	6dBm
Ths	Small Cell minimum distance Threshold	250m
T_W	Window size	10 frames
P_N	Noise Power (per RB)	-115.5 dBm
$R_{b,min}$	Minimum bit rate threshold	50 Kbps
$R_{b,max}$	Maximum bit rate threshold	300 Kbps

The results presented here are the average of 100 experiments, where in each experiment a different random user distribution has been considered. For each experiment a total of 1000 frames are simulated. The proposed strategy is compared against the classical CRE-ABS reference scheme where the macrocells are not allowed to transmit data in any of the ABS subframes and where the transmit power per RB of the macrocell is constant and equal to $P_{TM,i,high}$. In order to have a fair comparison, the reference scheme also considers the PF prioritization criterion and the $R_{b,min}$, $R_{b,max}$ limitations in the scheduling algorithm as in the proposed approach.

Scenario 1: In this scenario, the two small cells are located at distances 400 and 150 meters from the macrocell site, as seen in Figure 4-29(a). Correspondingly, since *Ths*=250m, the proposed algorithm performs the splitting in the frequency domain following Case 2 as indicated in the Section III. Figure 4-30, shows the gain in terms of average user capacity achieved by the proposed scheme with respect to the reference scheme, as a function of the number of users in the hotspot and for different values of the number of ABS subframes μ. As it can be observed, the proposed scheme offers a significant gain that increases with the number of ABS subframes, reaching a value of 45% for μ=6. A key element in achieving this gain is the adjustment of the number of reserved RBs ε according to the number of CRE users in the small cell. In particular, when the number of users in the hotspot (and correspondingly the number of users in the small cells) is small, the algorithm configures the number of reserved RBs ε for transmission in each ABS subframe to be also very small. In contrast, when the number of the small cell users is increased, the algorithm tends to increase the number of reserved RBs ε. In other words, the proposed solution can reconfigure the corresponding resources depending on the traffic load. Note also that in the cases where the number of the ABS subframes is small, for instance 1 or 2, the behavior of the proposed solution resembles that of the reference scheme, since in this case the algorithm leads to ε=*numRB*, meaning that, like in the reference scheme, the macrocell is not allowed to transmit in ABS subframes.

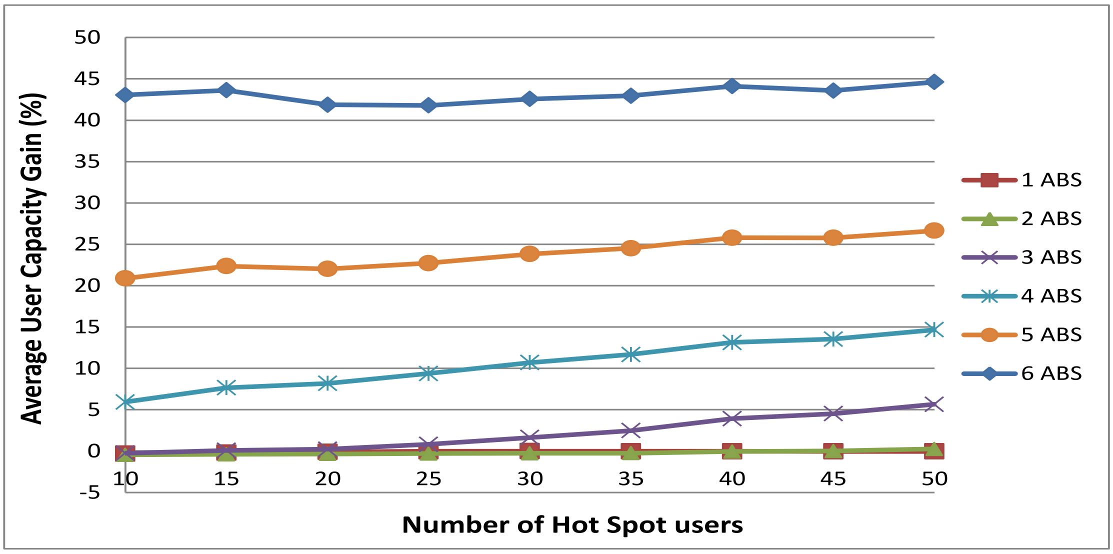

Figure 4-30: Average User Capacity Gain (%) in scenario 1

Figure 4-31 and Figure 4-32 present separately the capacity gains of the macro and small cell users, respectively. As it can be observed the macrocell users present a very high gain (up to 71%) in their capacity while the small cell users have a small loss (up to 18%), especially when the number of the hotspot users is low. This behavior reflects the good performance of the algorithm, since it is shown that when the load of the macrocell is heavy but the load of the small cells is low, the solution tends to utilize the available resources in such a way that compensates the uneven user distribution. Moreover, as the hotspot users increase, the RBs are configured in a way that still provides some resources to the heavily loaded macro cell, although without generating severe interference to the small cell users. As such, it is shown that the proposed solution can adapt to traffic load changes and balance the capacity among the two types of cells, while keeping the introduced interference to the small cell users in low levels.

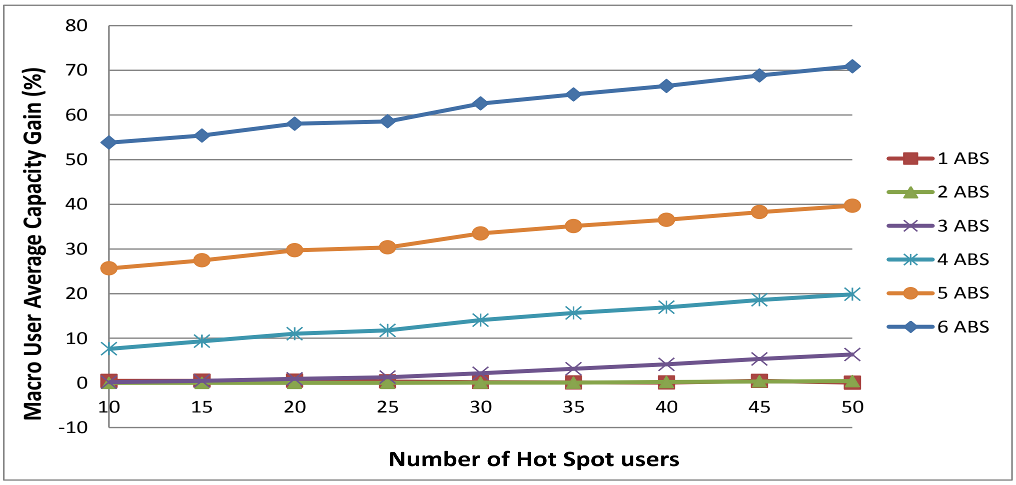

Figure 4-31: Macro Cell User Average Capacity Gain (%) in scenario 1

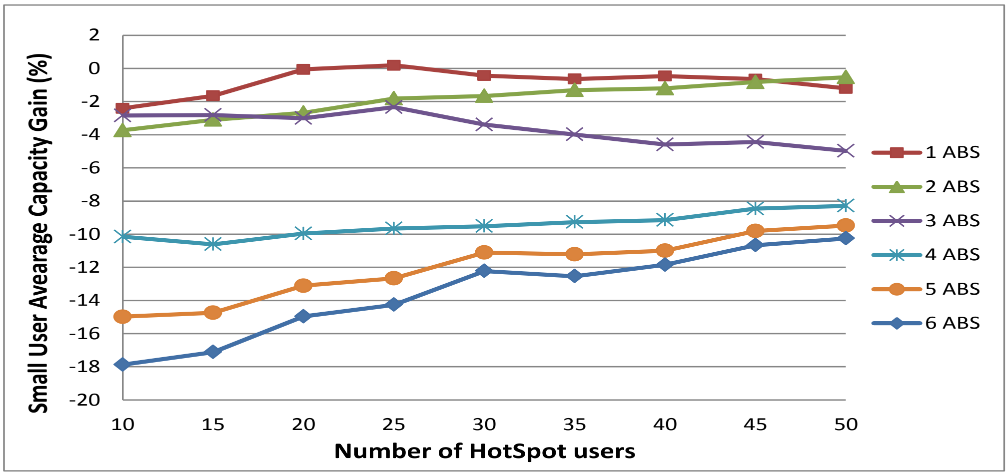

Figure 4-32: Small Cell User Average Capacity Gain (%) in scenario 1

Scenario 2: In this scenario, two small cells are located at 400 and 320 m from the macro BS, as seen in Figure 4-29(b). As such, their distance is above the defined threshold *Ths*=250 m and therefore Case 1 is applied, where two levels of transmit power are used for the macrocell. Figure 4-33 presents the average user capacity gain compared to the reference scheme in this case. It can be observed that the proposed strategy outperforms the classical approach, and the achieved gain increases with the number of ABS subframes μ, reaching a 16% gain for the case of μ=6. The benefit results from the fact that the proposed solution provides additional resources to the macro users with the corresponding increase of capacity.

In this scenario the gain achieved by the proposed algorithm is a bit lower than in scenario 1. The reason is that, on the one hand, macrocell inner users are assigned lower transmit power in the ABS subframes while at the same time they receive some interference from the small cell users, so this reduces the gain in the capacity of the macrocell compared to the case 2 applied in the previous scenario. On the other hand, the small cell users experience some capacity reduction; however in this case it is lower than in scenario 1, since the CRE users, instead of being assigned only reserved RBs, are allowed to transmit in all the RBs of the ABS subframes with the cost of some interference that is kept in low levels due to the far distance of the small cells from the macrocell.

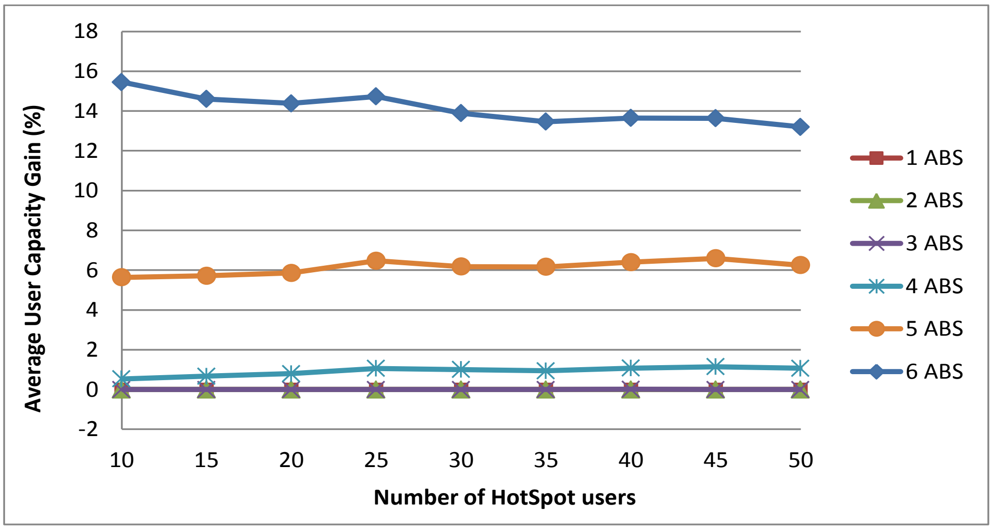

Figure 4-33: Average User Capacity Gain (%) in scenario 2

4.14.4 References

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4.15 Achievements JRA 1.3.3B – Energy-Aware Competitive Power Allocation for Heterogeneous Networks under QoS Constraints

4.15.1 Description

The major results that have been obtained within this research activity can be found in [1]-[4] and are summarized in the next. We consider the uplink of a HetNet where S low-range SCAs are adjoined to a macro-tier cell operating in an OFDMA-based open-access licensed spectrum. For compactness of notation, let us denote the macrocell base station (MBS) by index s = 0, so that $\mathcal{S} = \{0, 1, \ldots, S\}$ represents the set of HetNet receiving stations. The s-th cell uses a set of orthogonal subcarriers to serve the Ks user equipment (UE) falling within its coverage radius ρ_s. For simplicity, we assume that the same set of subcarriers $\mathcal{N} = \{1,\ldots,N\}$ is used by both tiers. We also assume that N is assigned by the network and cannot be controlled by the cell operators. Each cell AP is further equipped with M_s receiving antennas, whereas a single antenna is employed at the UE to keep the complexity of the front-end limited. The framework described in the paper can be generalized to the case of a multicellular HetNet scenario, including MIMO configurations, in a straightforward manner. Let $\mathbf{h}_{kj,n}$ denote the uplink channel vector with entries $[\mathbf{h}_{kj,n}]_m$ representing the (frequency) channel gains over subcarrier n from the j-th UE to the m-th receive antenna of the serving AP ψ(k) of user k, where $\psi(k) : \mathcal{K} \rightarrow \mathcal{S}$ is a generic function that assigns each user k its serving AP. In the following, $\mathcal{K} = \{1,\ldots,K\}$ and $K = \sum_{s=0}^{S} K_s$ denote the set and the number of UE in the network, respectively, where K_s represents the number of UE in the s-th cell: if s = 0, the UE will be termed macrocell user equipments (MUE), and small-cell user equipments (SUE) otherwise, although there is no substantial distinction among the two classed of users, as better clarified in the remainder of this work. To keep the complexity of the signal processing at the AP at a tolerable level, a simple linear detection scheme is employed for data detection, although a generalization to nonlinear detectors is straightforward. This means that the entries of vector $\mathbf{x}_{k,n}$ collecting the samples received over subcarrier n at the AP serving the k-th UE are linearly combined to form $y_{k,n} = \mathbf{g}_{k,n}^H\mathbf{x}_{k,n}$ where $\mathbf{g}_{k,n}$ is the vector k, employed for recovering the data transmitted by user k over subcarrier n. The SINR over the n-th subcarrier that is achieved by user k at its serving AP then takes the form:

$$\gamma_{k,n} = \mu_{k,n}(\mathbf{p}_{-k,n})p_{k,n} \tag{4.15.1}$$

where

$$\mu_{k,n}(\mathbf{p}_{-k,n}) = \frac{\left\|\mathbf{g}_{k,n}^H \mathbf{h}_{kk,n}\right\|^2}{\left\|\mathbf{g}_{k,n}\right\|^2 \sigma^2 + \sum_{j=1, j\neq k}^{K} \left\|\mathbf{g}_{k,n}^H \mathbf{h}_{kj,n}\right\|^2 p_{j,n}} \tag{4.15.2}$$

Using (4.15.1) the achievable rate (normalized to the subcarrier bandwidth, and thus measured in b/s/Hz) of the k-th user will then be:

$$r_k(\mathbf{p}) = \frac{1}{N}\sum_{n=1}^{N} \log_2(1+\gamma_{k,n}) \tag{4.15.3}$$

where $\mathbf{p}_k = [p_{k,1}, p_{k,2}, \ldots, p_{k,N}]^T$ denotes the power vector of user k over all subcarriers n = 1,...,N, and $\mathbf{p} = (\mathbf{p}_1, \ldots, \mathbf{p}_K)$ is the corresponding power profile for all users (obviously, $p_{k,n} = 0$ if user k is not transmitting over subcarrier n). Note that the multiple access interference (MAI) of user k comes from both intra-cell interference (generated by other UE served by the same AP) and inter-cell interference (from UE served by all other APs). To simplify the notation, the argument of $\mu_{k,n}$ and r_k will be suppressed in what follows.

The energy-efficient design of the network design must take into account the energy consumption incurred by each UE. To that end, note that in addition to the radiated powers p_k at the output of the radio-frequency front-end, each terminal k also incurs circuit power consumption during transmission, mostly because of power dissipated at the UE signal amplifier. Therefore, the overall power consumption $P_{T,k}$ of the k-th UE will be given by

$$P_{T,k} = p_{c,k} + \sum_{n=1}^{N} p_{k,n} = p_{c,k} + P_k \tag{4.15.4}$$

where P_k is the transmitted power of user k over the entire spectrum, while $p_{c,k}$ represents the average power consumed by the device electronics of the k-th UE (assumed for simplicity to be independent of the transmission state). The energy efficiency of the link can then be measured (in b/J/Hz) by the utility function

$$u_k(\mathbf{p}) = \frac{r_k}{P_{T,k}} = \frac{1}{N} \frac{\sum_{n=1}^{N} \log_2(1+\mu_{k,n} p_{k,n})}{p_{c,k} + \sum_{n=1}^{N} p_{k,n}} \tag{4.15.5}$$

where the dependence on the transmit power vectors of all other users is subsumed in the gains $\{\mu_{k,n}\}$. Accordingly, in data-oriented wireless networks, QoS requirements take the form $r_k \geq \theta_k$ where θ_k is the minum rate threshold required by user k. To summarize, the design of an energy-efficient resource allocation scheme which encompasses both subcarrier allocation and power control amounts to the multi-agent, multi-objective optimization problem:

$$\begin{aligned} &\max_{\mathbf{p}_k} && u_k(\mathbf{p}) \quad \forall k \\ &\text{subject to} && \frac{1}{N}\sum_{n=1}^{N} \log_2(1+\mu_{k,n} p_{k,n}) \geq \theta_k \end{aligned} \tag{4.15.6}$$

Unlike other OFDMA resource allocation problems subcarrier selection and power loading are tackled in a *joint* manner. Furthermore, inter- and intra- cell interference between UE makes (4.15.6) into a game where each UE $k \in \mathcal{K}$ aims at unilaterally maximizing its individual link energy-efficiency via an optimal choice of power allocation vector $\mathbf{p}_k$ – and, in so doing, obviously affects the possible choices of all other UE in the network.

The major challenge in this formulation is represented by the minimum-rate requirements that cast the problem into a non-cooperative game in the sense of Debreu in which the actions sets of the players are coupled (and not independent as in the more popular Nash games). We used fractional programming techniques to characterize the game's equilibrium states (when they exist) as the fixed points of a water-filling operator. To attain this equilibrium in a distributed fashion, we also proposed an adaptive, distributed algorithm based on an iterative water-filling best response process and we provided sufficient conditions for its convergence. The convergence and the performance of our method was further assessed by numerical simulations: performance results show that reducing the non-radiative power consumed by the user device electronics, offloading the macrocell traffic through small cells, and increasing the number of receive antennas, are particularly critical to improve the performance of mobile terminals in terms of *both energy efficiency and spectral efficiency*.

Using a reasonable simulation setup, we showed that the proposed framework is able to achieve significantly high area spectral efficiencies (larger than 1, 000 b/s/Hz/km^2), peak and cell-edge spectral efficiencies (up to 6 b/s/Hz and around 0.5 b/s/Hz, respectively), and energy efficiencies (several Mb/J), while considering dense populations of users (around 1, 000 users/km^2), low power consumptions (at most some Watts), a limited number of antennas (at most 8 for the small-cell access points and 16 for the macrocell base station), and a simplified signal processing at the receiver (maximal ratio combining).

The system model adopted is general enough to encompass a more general *multi- cellular* and *multi-tier* network, and the derived approach can be thus automatically adapted to such scenarios. Moreover, distinguishing features of the proposed distributed algorithm are its *scalability* and *flexibility*, thus making it suitable to exploit all the available degrees of freedom of the network and to be adapted to emerging 5G technologies, such as ultra-densification and massive MIMO.

4.15.2 References

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4.16 Achievements JRA 1.3.3B – Energy-Efficient Power Optimization in Heterogeneous Networks: A Quasi-Variational Inequality Approach

4.16.1 Description

The major results that have been obtained within this research activity can be found in [1] and [2] and are summarized in the next. Consider a K−user N−parallel Gaussian interference channel, in which there are K transmitter-receiver pairs sharing N parallel Gaussian subchannels, that might represent time or frequency bins. The channel transfer function over the *n*th subchannel between the transmitter i and receiver *k* is denoted by $H_{k,i}(n)$. The transmission strategy of each user *k* is the power allocation vector $\mathbf{p}_k = [p_k(1), p_k(2), \ldots, p_k(N)]^T$ over the *N* subchannels satisfying the following (local) transmit power constraints: $P_k = \{\mathbf{p}_k \in \mathbb{R}_+^N ; h_k(\mathbf{p}_k) \leq 0\}$ where $h_k(\mathbf{p}_k)$ is an affine function of $\mathbf{p}_k$ given by $h_k(\mathbf{p}_k) = \mathbf{1}^T \mathbf{p}_k - P_k^{\max}$ with $P_k^{\max}$ being the total power available at transmitter *k*. We assume that the *K* transmitter-receiver pairs do not cooperate with each other and that the multi-user interference is simply treated as additive colored noise at each receiver. Moreover, local perfect channel state information is available at both transmitter and receiver sides. In the above circumstances, the maximum achievable rate on link *k* for a specific power allocation profile $\mathbf{p} = [\mathbf{p}_1^T, \mathbf{p}_2^T, \ldots, \mathbf{p}_K^T]^T$ is given by

$$R_k(\mathbf{p}_k, \mathbf{p}_{-k}) = \sum_{n=1}^{N} \log\left(1 + \frac{|H_{k,k}(n)|^2 \, p_k(n)}{\sigma_k^2(n) + \sum_{i \neq k} |H_{i,k}(n)|^2 \, p_k(n)}\right) \tag{4.16.1}$$

Where $\sigma_k^2(n)$ is the noise variance over the *n*th subcarrier on link *k* and $\mathbf{p}_{-k} = [\mathbf{p}_1^T, \ldots, \mathbf{p}_{k-1}^T, \mathbf{p}_{k+1}^T, \ldots, \mathbf{p}_K^T]^T$ collects the power allocation vectors of all transmitters, except the *k*th one. The energy efficiency $E_k(\mathbf{p}_k, \mathbf{p}_{-k})$ of the *k*th link can be computed as

$$E_k(\mathbf{p}_k, \mathbf{p}_{-k}) = \frac{R_k(\mathbf{p}_k, \mathbf{p}_{-k})}{\Psi_k + 1^T p_k} \tag{4.16.2}$$

with $\Psi_k > 0$ being the RF circuitry power consumed at transmitter *k*. Assume a heterogeneous scenario in which a set K_R of players follows a rate maximization strategy, while the remaining set K_E is interested in maximizing its own EE. Let us define $G = \langle K, \{P_k\}, \{u_k\} \rangle$ the corresponding game in which: $K = K_R \cup K_E$ is the set collecting both types of users; the strategy set P_k is the power available at transmitter *k*; and u_k is the utility function, defined as

$$\mu_k = \begin{cases} R_k(\mathbf{p}_k, \mathbf{p}_{-k}) & k \in K_R \\ E_k(\mathbf{p}_k, \mathbf{p}_{-k}) & k \in K_E \end{cases} \tag{4.16.3}$$

The problem to be solved for each player *k* can thus be mathematically formalized as follows:

$$\begin{array}{ll} \max\limits_{\mathbf{p}_k} & \mu_k(\mathbf{p}_k, \mathbf{p}_{-k}) \quad \forall k \\ \text{subject to} & \mathbf{p}_k \in P_k \end{array} \tag{4.16.4}$$

and the corresponding Nash equilibria are obtained as follows. First, the maximization problem is reformulated as a QVI using convex fractional programming theory. This provides us with all the mathematical tools to study the uniqueness of the NE points of the heterogeneous game, and the convergence properties of iterative algorithms. In particular, we first propose a *centralized* approach, which relies on an iterative method for solving QVIs whose convergence is guaranteed under mild assumptions. Then, we propose an alternative solution exploiting the equivalence between the QVI and a NCP, which gives each pair the possibility to reach the NE in a *distributed* manner without the need for any centralized processing.

Numerical results are used to assess the performance of the proposed solutions when applied to a heterogeneous network. In particular, we consider a scenario with $K = 8$ players in which four of them aim at maximizing the EE and the other four are focused on the SE maximization. The system parameters are as follows: *i)* the interference channel is composed of $N = 16$ subchannels; *ii)* the channel coefficients $H_{k,i}(n)$ are assumed to be Gaussian random variables with zero mean and unit variance; *iii)* the average SNR on the generic subchannel n over link k is set to 0 dB; *iv)* the maximum normalized power is fixed to N for any k; *v)* the static power consumption is assumed to be 1 for all k; *vi)* the starting point of the distributed algorithms is the uniform power allocation strategy.

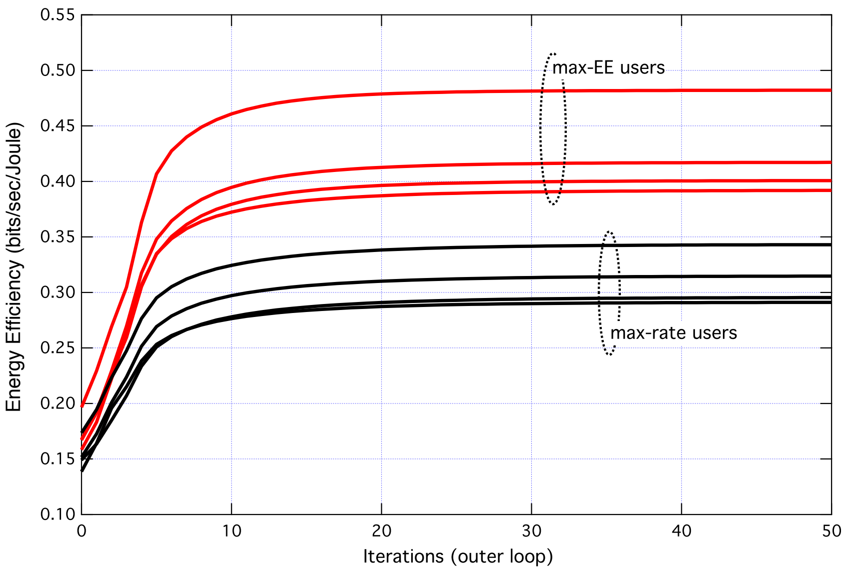

Figure 4-34: Energy efficiency dynamics when SIR = 3 dB

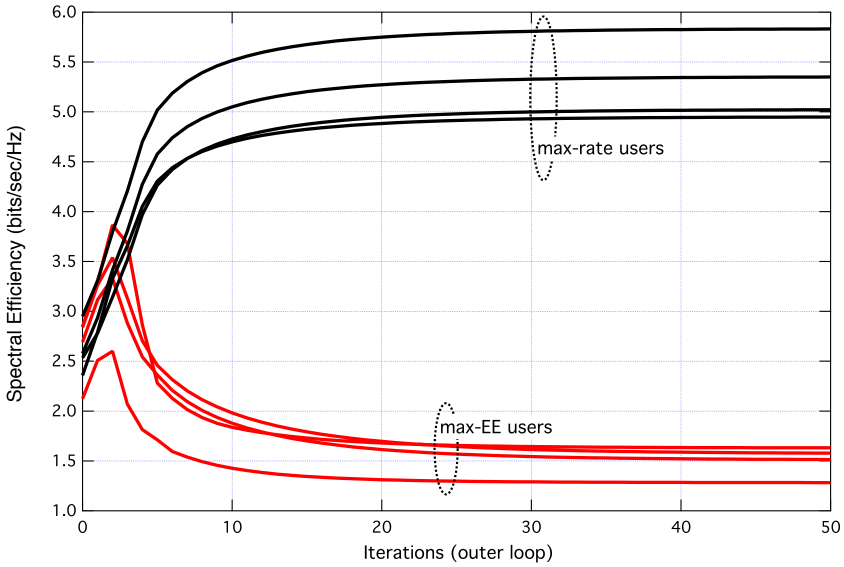

Figure 4-35: Spectral efficiency dynamics when SIR = 3 dB

Figure 4-34 and **Figure 4-35** show respectively the EE and the SE dynamics during the time interval needed by the proposed algorithm to converge. As it is seen, a stable power allocation strategy is achieved while enhancing the EE of the energy efficient users up to the 113% at the price of a consistent information rate loss. The equilibrium is also achieved for the SE users with a final SE more than doubled with respect the initial uniform power allocation.

4.16.2 References

[1] G. Bacci, V. Belmega, L. Sanguinetti “Distributed energy-efficient power optimization in cellular relay networks with minimum rate constraints”, IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Florence, Italy, May 2014.

[2] I. Stupia, L. Sanguinetti, G. Bacci, L. Vanderdorpe “Distributed Energy-Efficient Power Optimization for Relay-Aided Heterogeneous Networks”, International Workshop on Wireless Networks (WiOpt - WCN), Hammamet, Tunisia, May 2014.

4.17 Achievements JRA 1.3.3B – Distributed power control over interference channels using ACK/NACK feedback

4.17.1 Description

The major results that have been obtained within this research activity can be found in [1] and are summarized in the next. We consider a K−user Gaussian interference channel, in which there are K transmitter-receiver pairs sharing the same Gaussian channel that might represent a time or frequency bin. The transmission takes place at the same time over the same frequency band and it is organized in frames. Each frame counts a certain number of packets, each one composed of M data symbols of unity-energy. We call $x_k(m)$ the mth data symbol of transmitter k within a generic packet and denote $\boldsymbol{x}_k = [x_k(1),x_k(2),...,x_k(M)]^T$. Each $\boldsymbol{x}_k$ is encoded at a rate $r_k \in R_k$ with R_k being the set of feasible rates and transmitted with an amount of power $p_k > 0$. The channel is assumed to be constant over a frame and to change independently from one frame to another (block-fading channel). We assume that the transmitters do not have any a-priori knowledge of the channel. Letting $h_{k,i}$ denote the channel coefficient between transmitter *i* and receiver *k* over a generic packet, the SINR at the *k*th receiver within the generic packet can be written as

$$\gamma_k = \frac{\left|h_{k,k}\right|^2 p_k}{\sigma_k^2 + \sum_{i \neq k} \left|h_{k,i}\right|^2 p_i} \tag{4.17.1}$$

For later convenience, we call $\mu_k = \gamma_k / p_k$ the CINR and denote $\mathbf{p}_{-k} = [p_1,\ldots,p_{k-1},p_{k+1},\ldots,p_K]^T$ the vector collecting all the transmit power except that of transmitter *k*. In this work, we aim at solving for any $k = 1,2,\ldots,K$ the following power minimization problem

$$\begin{array}{ll} \min\,(p_k) & p_k \\ subject\ to & \gamma_k \geq \overline{\gamma_k} \end{array} \tag{4.17.2}$$

Where γ_k are given QoS requirements. The interplay among the pairs leads to a multidimensional optimization problem in which each transmitter-receiver pair aims at unilaterally choosing the minimum transmit power p_k so as to full fill its own requirement. In doing this, each pair affects the choice of all other pairs as well. The natural framework to study the solution of problems in the above form is non-cooperative game theory. In this case, the solution concept to be used is the GNE that is defined as the point collecting all the system states stable to unilateral deviations. The GNE of the power allocation problem has been extensively studied in the literature. The main results are summarized in the following theorem.

Theorem 1: *If the problem (4.17.2) is feasible, then there exists a unique power allocation vector* $\mathbf{p}^* = [p_1^*, p_2^*, \ldots, p_K^*]^T$ *that is the GNE of the game. The elements of* $\mathbf{p}^*$ *are the solutions to the following fixed-point system of equations:*

$$p_k^* = BR(p_{-k}^*) = \frac{\overline{\gamma_k}}{\mu_k(p_{-k}^*)} \quad \forall k \tag{4.17.3}$$

where the operator BR stands for the best-response of user k to given other users' strategy p_{-k}^*.

In addition to the results above, it can be shown that the optimal point $\mathbf{p}^*$ can be reached via a distributed iterative power control policy based on best response dynamics according to which every player *k* updates its power (strategy) $p_k^{(n+1)}$ at *k* time *n+1* as

$$p_k^{(n+1)} = \frac{\overline{\gamma_k}}{\mu_k(p_{-k}^{(n)})} = p_k^{(n)} \frac{\overline{\gamma_k}}{\gamma_k(p^{(n)})} \tag{4.17.4}$$

from which it follows that the computation of $p_k^{(n+1)}$ for a given $\mathbf{p}_{-k}^{(n)}$ requires knowledge of $\gamma_k(p^{(n)})$. Most of the existing works rely on the assumption that each transmitter has perfect knowledge of it. Unfortunately, this assumption does not hold true in practical applications and the only way for the transmitter to acquire this knowledge is through a return control channel. Although possible, however, this solution is not compliant with current cellular standards in which the receiver only sends back an ACK ($f_k = 0$) whenever is able to correctly decode the packet and a NACK ($f_k = 1$) otherwise. Assume that a maximum likelihood (ML) decoder is used at the receiver and denote by $\hat{\mathbf{x}}_k$ the ML estimate of $\mathbf{x}_k$ obtained from $\mathbf{y}_k$. Assuming Gaussian random codes ML decoding error probability ε_k (μ_k, r_k, p_k) can be approximated as follows

$$\varepsilon_k(\mu_k, r_k, p_k) \approx \exp\left(M\rho \left[r_k \log 2 - \frac{1}{2}\log\left(1 + \frac{\gamma_k}{1+\rho}\right)\right]\right) \tag{4.17.5}$$

where $\rho \in [0,1]$ is the union bound parameter and *M* is the number of data symbols per packet encoded at a rate of r_k bits/symbol. Based on the above considerations, we propose an iterative and distributed two-step algorithm that allows each transmitter-receiver pair to reach the GNE of the game only exploiting the knowledge of $\{p_k^{(n-1)}, r_k^{(n-1)}, f_k^{(n-1)}$. The first step aims at locally computing a reliable estimate $\hat{\mu}_k^{(n)} of\ \mu_k^{(n)}$. The value of $\hat{\mu}_k^{(n)}$is used to update $r_k^{(n)}$ and the transmit power as specified in (4.17.4). The analytical study of the convergence of the proposed algorithm is still much open and left for future work. In the next section, we limit to assess the convergence of the aglorithm by means of Monte Carlo simulations. Interestingly, it turns out that the proposed solution converges (within the required accuracy) whenever the game with complete information is feasible and thus the existence of the unique GNE point is guaranteed. Moreover, the convergence point is the same meaning that the same performance can be achieved despite the amount of required information is much lower. The only price to pay is a greater convergence time.

The performance of the distributed algorithm is now assessed by means of an extensive simulation campaign. To this end, we consider the uplink of a small-cell network consisting of up to *K* = 6 single-antenna small cells, each serving a single UE. We set $\bar{\gamma} = [0.5,1,1.5,2,2.5,3]^T$ dB and assume that the coverage area of each small cell is circular with radius 50 m and minimum distance 5 m. The small cells are randomly distributed over a 200 × 50*K* area.

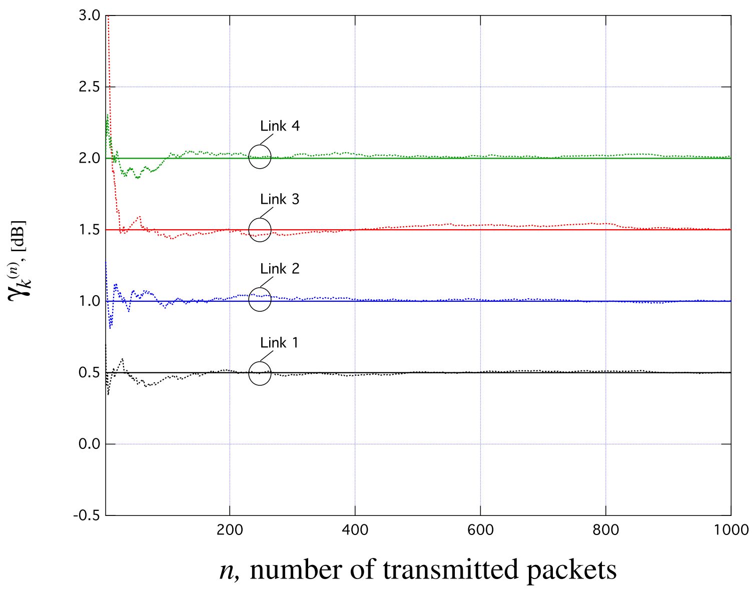

Figure 4-36: SINR vs. number of packets when *K* = 4

Figure 4-36 illustrates the values of $\gamma_k^{(n)}$ (dashed lines) measured at the BS as a function of the number *n* of transmitted packets in a scenario of *K* = 4 small cells. The target SINRs are also reported (continuous lines) for comparison. **Figure 4-37** reports also the variations of $p_k^{(n)}$ (dashed lines) as *n* increases together with the power (continuous lines) required at the GNE point. As seen, in both cases, $\gamma_k^{(n)}$converges to the target SINR $\overline{\gamma_k}$ within 200 packets. Interestingly, the attained power level is exactly the same achieved at the GNE point of the game with complete information.

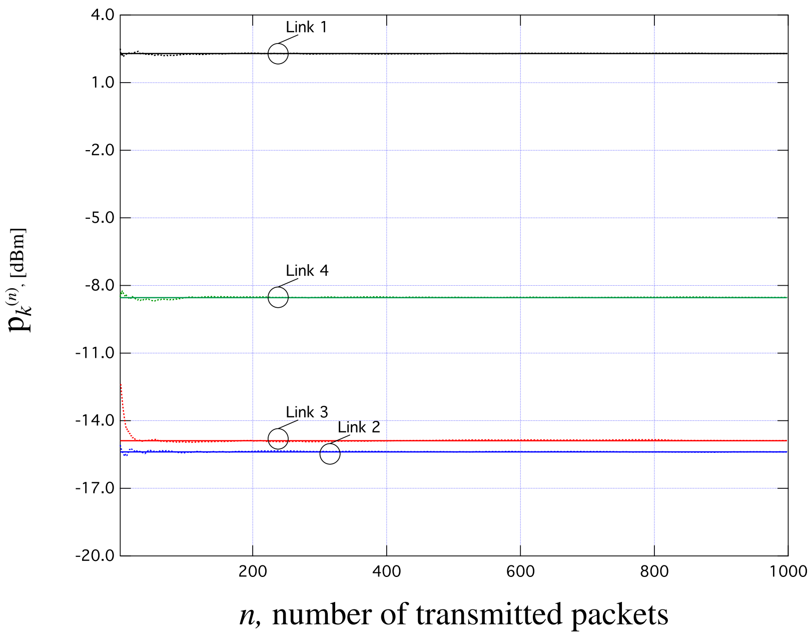

Figure 4-37: Power vs. number of packets when $K = 4$

4.17.2 References

[1] R. Andreotti, L. Marchetti, L. Sanguinetti, M. Debbah 'Distributed power control over interference channels using ACK/NACK feedback', *IEEE Global Communications Conference (GLOBECOM)*, Austin, Texas, Dec. 2014.

4.18 Achievements JRA 1.3.3.B – Distributed energy-efficient power optimization in BICM-OFDM systems

4.18.1 Scenario and system model

Small-cell scenario

The scenario under analysis, depicted in **Figure 4-38**, is the uplink of Q small cells (SCs) belonging to the set $\mathcal{Q} \triangleq \{1,\ldots,Q\}$ and operating in OFDMA technology. Each SC exploits the same frequency band B, made of N subcarriers in the set $\mathcal{N} \triangleq \{1,\ldots,N\}$. In every SC, K_q users, in the set $\mathcal{K}_q \triangleq \{1,\ldots,K_q\}$, transmit to the relevant SBS over orthogonal subbands according to the OFDMA-based access, so that intra-cell interference is avoided. Accordingly, let us denote with $\mathcal{N}_{k,q}$ the set of subcarrier assigned to user k in cell q, such that $\mathcal{N}_{k,q} \cap \mathcal{N}_{j,q} = \varnothing$, $\forall j \in \mathcal{K}_q \setminus \{k\}$, and $\bigcup_{k \in \mathcal{K}_q} \mathcal{N}_{k,q} \subseteq \mathcal{N}$. However, they can suffer from inter-cell interference, as shown in **Figure 4-38**. Interference cancelation techniques are not considered here as they would require a sizeable decoding complexity and a greater quantity of signaling information among the SCs, and therefore in the following the inter-cell interference perceived at every SBS will be considered as additive colored noise.

BIC-OFDM link and link performance prediction

The generic uplink between user $k \in \mathcal{K}_q$ and SBS $q \in \mathcal{Q}$ is a conventional BIC-OFDM link employing coding rate $r_{k,q} \in \mathcal{D}_r$, being $\mathcal{D}_r$ the set of feasible coding rates, and (unitary-energy) modulation symbol per subcarrier n $x_{k,q,n} \in 2^{m_{k,q,n}}$-QAM, being $m_{k,q,n} \in \mathcal{D}_m \triangleq \{2, \ldots, m_{\max}\}$ the number of bits allocated on the nth subcarrier, if $n \in \mathcal{N}_{k,q}$, and $x_{k,q,n} = 0$ if $n \notin \mathcal{N}_{k,q}$. Every symbol is transmitted with a power $p_{k,q,n}$ in a way that the power allocation (PA) vector $p_{k,q} \triangleq [p_{k,q,1}, \ldots, p_{k,q,N}]^T$ satisfies the available power limit $P_{k,q}$ as follows: $\sum_{n \in \mathcal{N}_{k,q}} p_{k,q,n} \le P_{k,q}$. At the qth SBS, the user k post-processing SINRs vector is $\boldsymbol{\Gamma}_{k,q} \triangleq \mathbf{p}_{k,q} \odot \boldsymbol{\gamma}_{k,q}$ (the operator $\odot$ denotes the element-wise multiplication), where $\boldsymbol{\gamma}_{k,q} \triangleq [\gamma_{k,q,1}, \ldots, \gamma_{k,q,N}]^T$ and

$$\gamma_{k,q,n} \triangleq \frac{|h_{k,q,q,n}|^2}{\sigma^2_{w_{k,q,n}} + \sum_{s \neq q} \sum_{j \in \mathcal{K}_s} p_{j,s,n} |h_{j,s,q,n}|^2} \quad \forall n \in \mathcal{N}_{k,q}, \tag{4.18.1}$$

0 otherwise, being $h_{j,s,q,n}$ the channel coefficient between user j in cell s and SBS q over subcarrier n and $\sigma^2_{w_{k,q,n}}$ the variance of the zero-mean complex-valued Gaussian random variable describing the ambient noise. In particular, the second term at the denominator represents the intra-cell interference perceived at SBS q by user k.

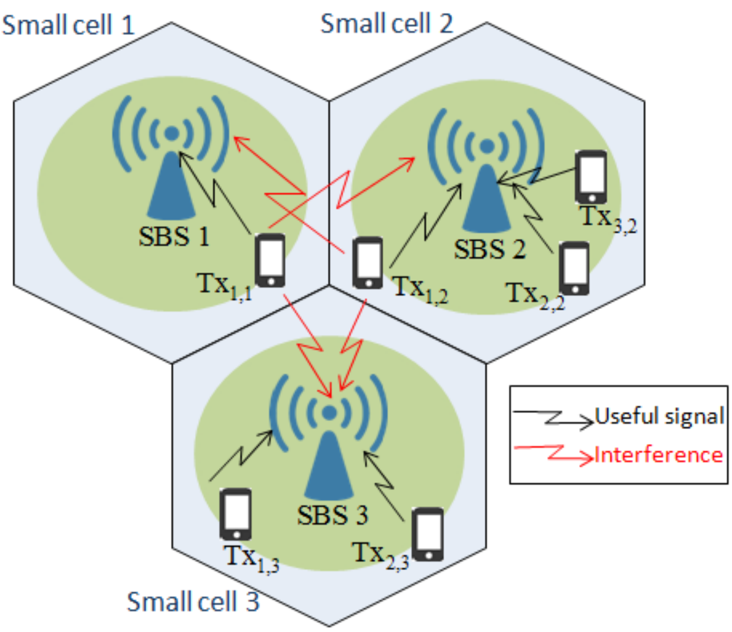

Figure 4-38: Small cell scenario with $Q = 3$ SCs

For the packet-oriented systems described above, where practical modulation and coding schemes are employed, a suitable figure of merit is clearly the PER. Though, since the fading channel introduces large SINR variations across the subcarriers, a closed form expression of the PER can not be derived. An effective solution is offered by the ESM technique [1], which one-to-one maps the SINR vector $\boldsymbol{\Gamma}_{k,q}$ of the kth user in cell q into a single scalar value $\gamma_{k,q}$, named ESNR, representing the SNR experienced by an equivalent coded BPSK system transmitting over an AWGN channel. More precisely, the ESNR $\gamma_{k,q}$ is such that $\mathrm{PER}_{r_{k,q}}(\mathbf{\Gamma}_{k,q}) = \Phi_{r_{k,q}}(\gamma_{k,q})$, where $\mathrm{PER}_{r_{k,q}}$ and $\Phi_{r_{k,q}}$ denote the PER of the frequency-selective coded BIC-OFDM system and that of the equivalent coded binary system over AWGN channel, respectively, when both employ code rate $r_{k,q}$. The PER $\Phi_{r_{k,q}}$, according to [2], [3], is an analytic, monotonically decreasing, and convex function in the region of interest. Before proceeding further, let us introduce the following useful definitions that allow to ease the notation without loss of generality. Recalling that, due to the OFDMA-based access at most one user per cell transmits over a given subcarrier, the interfence caused over the band $\mathcal{B}$ by the generic SC s towards the other SCs, depends on the "global" SC power and channel vectors $\mathbf{p}_s \triangleq [p_{s,1},\ldots,p_{s,N}]^{\mathrm{T}}$ and $\mathbf{h}_{s,q} \triangleq [h_{s,q,1},\ldots,h_{s,q,N}]^{\mathrm{T}}$, where $\mathbf{p}_s \equiv \sum_{j\in\mathcal{K}_s} \mathbf{p}_{j,s} \odot \mathbf{a}_{j,s}$ and $\mathbf{h}_{s,q} \equiv \sum_{j\in\mathcal{K}_s} \mathbf{h}_{j,s,q} \odot \mathbf{a}_{j,s}$, being $\mathbf{a}_{j,s} = [a_{j,s,1},\ldots,a_{j,s,N}]^{\mathrm{T}}$ the subcarrier allocation vector for user j in SC s, i.e., $a_{j,s,n} = 1$ if $n \in \mathcal{N}_{j,s}$, 0 otherwise. In other words, concerning the inter-cell interference, each SC s behaves as composed by one virtual user transmitting with power $\mathbf{p}_s$ and denoted by the channel between him and the qth SC $\mathbf{h}_{s,q}$. Assuming uniform bit loading, that is, $m_{k,q,n} = m_{k,q} \in \mathcal{D}_{\mathrm{m}}$, $\forall n \in \mathcal{N}_{k,q}$, according to the ESM technique based on the cumulant moment generating function of the log-likelihood metrics at the input of the soft decoder, or κ ESM for short, the ESNR $\gamma_{k,q}$ is evaluated, as shown in [4], as

$$\gamma_{k,q}(\mathbf{p}_{k,q},\mathbf{p}_{-q}) \triangleq -\log\left(\frac{\displaystyle\sum_{n\in\mathcal{N}_{k,q}} \sum_{\mu=1}^{\sqrt{2^{m_{k,q}}}/2} \alpha_{k,q,\mu}\, e^{-\frac{p_{k,q,n}}{\rho_{k,q,n,\mu}(\mathbf{p}_{-q,n})}}}{N_{k,q} m_{k,q}} \right), \tag{4.18.2}$$

where $N_{k,q} = |\mathcal{N}_{k,q}|$, $\mathbf{p}_{-q} \triangleq [\mathbf{p}_1^{\mathrm{T}},\ldots,\mathbf{p}_{q-1}^{\mathrm{T}},\mathbf{p}_{q+1}^{\mathrm{T}},\ldots,\mathbf{p}_Q^{\mathrm{T}}]^{\mathrm{T}}$ and $\mathbf{p}_{-q,n} \triangleq [p_{1,n},\ldots,p_{q-1,n},p_{q+1,n},\ldots,p_{Q,n}]^{\mathrm{T}}$ collect the per-SC PA vectors and per-SC/per-subcarrier PA coefficients except those of SC q, respectively, $\rho_{k,q,n,\mu}(\mathbf{p}_{-q,n}) \triangleq \psi_{k,q,\mu} / \gamma_{k,q,n}(\mathbf{p}_{-q,n})$ and $\alpha_{k,q,\mu}$ and $\psi_{k,q,\mu}$ are constant values related the modulation size adopted by the kth user in cell q.

It is worth remarking that, when dealing with packet-oriented systems, users are interested in correctly receiving the entire packet, which is in fact the basic unit of information, and not only a part of it. Thus, the energy efficiency (EE) will depend on the successful transmitted rate, given by the product of the transmission rate and the packet success rate (PSR). This issue, which has been addressed in different scenarios, is still an open problem in (BICM-) OFDM systems where practical modulation and coding schemes are employed. In fact, the work in [5] relies on the theoretical assumption of Gaussian codebooks, whereas in [6] the overall successful transmit rate is given by the sum of the successful transmit rate per subcarrier, which is different than considering the PSR. The latter, whose expression is $\Psi_{r_{k,q}}(\gamma_{k,q}) = 1 - \Phi_{r_{k,q}}(\gamma_{k,q})$, is in fact a "global" metric that cannot be obtained as a linear expression of the successful probabilities of each subcarrier, as can be inferred from eqn. (4.18.2). In the following, we will refer to the proposed metric as goodput, i.e., the number of information bits delivered in error-free packets per unit of time, that is

$$\zeta_{k,q}(\mathbf{p}_{k,q},\mathbf{p}_{-q}) = \zeta_{k,q}^{(0)} r_{k,q} \sum_{n\in N_{k,q}} m_{k,q,n} \Psi_{r_{k,q}}(\gamma_{k,q}(\mathbf{p}_{k,q},\mathbf{p}_{-q})), \tag{4.18.3}$$

with $\zeta_{k,q}^{(0)}$ being a constant accounting for the ratio between the payload bits and the total transmitted bits (i.e., payload and headers bits). Thus, for a given pair of modulation and coding rate, the EE of the kth link in SC q subject to a target QoS $\bar{\zeta}_{k,q}$, i.e., $\zeta_{k,q}(\mathbf{p}_{k,q},\mathbf{p}_{-q}) = \bar{\zeta}_{k,q}$, $\forall k,q$, can be written as [7]

$$\begin{array}{ll} \min\limits_{\mathbf{p}_{k,q}^{(\min)} \le \mathbf{p}_{k,q} \le \mathbf{p}_{k,q}^{(\max)}} & \sum\limits_{n\in N_{k,q}} p_{k,q,n} \\ \text{s.t.} & \zeta_{k,q}(\mathbf{p}_{k,q},\mathbf{p}_{-q}) = \bar{\zeta}_{k,q} \end{array} ,\forall k,q,. \tag{4.18.4}$$

where $\mathbf{p}_{k,q}^{(\min)} \hat{=} [p_{k,q,1}^{(\min)}, \ldots, p_{k,q,N}^{(\min)}]^{\mathrm{T}}$ and $\mathbf{p}_{k,q}^{(\max)} \hat{=} [p_{k,q,1}^{(\max)}, \ldots, p_{k,q,N}^{(\max)}]^{\mathrm{T}}$ denote a power allocation mask per SC users, i.e., the minimum and maximum value of power per subcarrier.

PA in Point-to-Point BIC-OFDM link

Before analyzing the multiple-access channel case, let us focus on the point-to-point communication link scenario, that is $Q=1$ and $K_1=1$ (for this reason in the reminder of this section, the index q and k will be neglected in the quantities of interest). The aim is to satisfy over the link a given QoS, expressed in terms of a target GP value $\bar{\xi}$ (bit/OFDM symbol), saving as much power as possible, as described by eqn. (4.18.4). To this end, the transmission parameters to set are the modulation order over the active subcarriers, coding rate and power allocation vector. It is worth pointing out that, even if uniform bit loading is employed, the choice of the active subcarriers entails a bit loading procedure, in that the bit allocation vector m will be such that its nth component is $m_n = m$ if n is an active subcarrier, $m_n = 0$ otherwise. Moreover, the bit loading and power allocation problem cannot be jointly addressed, since this problem would be NP-hard. Thus, considering a given choice of modulation order, i.e., bit-per-subcarrier m, and coding rate r, a given QoS constraint $\bar{\xi}$ and the SNR vector γ, this problem can be efficiently tackled in two steps as follows.

1) For the first step, the bit loading procedure, originally proposed in [8], is applied with the set of feasible bit per subcarrier being $\mathrm{D}_{\mathrm{m}} = \{0, m\}$. As result, we get N bit allocation vectors $\{m^{(n)}\}_{n=1}^{N}$, where $m^{(n)}$ is the best bit allocation vector with n active subcarriers when SNR vector γ is experienced. If $\bar{N} \le N$ is the lowest integer such that $rm\bar{N} \ge \bar{\xi}$, the bit allocation vector turns to be $m = m^{(\bar{N})}$.

2) In the second step, the only optimization variable left is the PA vector $\mathbf{p}$. The aim now is to minimize the total PA guaranteeing at the same time the QoS constraint, i.e., a value of GP $\bar{\xi}$, as described by (4.18.4).

The PA problem in point 2, as shown in [7], can be recast into the following optimization problem

$$\begin{array}{ll} \min\limits_{\mathbf{0} \le \mathbf{p} \le \bar{\mathbf{p}}^{(\max)}} & \sum\limits_{n\in N} p_n \\ \text{s.t.} & \sum\limits_{\in N} \sum\limits_{\mu=1}^{\sqrt{2^m}/2} \alpha'_{n,\mu} e^{-\frac{p_n}{\rho_{n,\mu}}} \le \kappa \end{array} \tag{4.18.5}$$

where $\alpha'_{n,\mu} \stackrel{\Delta}{=} \alpha_\mu \cdot e^{-p_n^{(\min)}/\rho_{n,\mu}}$, $\bar{p}_n^{(\max)} \stackrel{\Delta}{=} p_n^{(\max)} - p_n^{(\min)}$, and $\kappa \stackrel{\Delta}{=} Nme^{-\gamma^*}$, with

$$\gamma^* \stackrel{\Delta}{=} \Psi^{-1}\left(\bar{\xi} / (\zeta^{(0)} rNm)\right). \tag{4.18.6}$$

Thus, for a given modulation and coding pair, the QoS constraint expressed in terms of target GP in (4.18.4) can be rewritten in terms of the equivalent QoS constraint in terms of target effective SNR γ^* in (4.18.6).

Thus, looking at both the objective function (linear) and the constraints (convex) of (4.18.5), the latter results a convex optimization problem. Unfortunately, due to the QoS constraint, it is not possible to obtain a closed-form solution. The optimal solution can be found via conventional numerical methods [9], with the drawback of being computationally heavy. Hence, in the following we propose an alternative method to get a closed-form solution of (4.18.5), whereas the results obtained with the numerical approach will be used as benchmark. To this end, let us focus on the following design guidelines.

1) Following the line of reasoning proposed in [4], where the problem of finding the PA vector maximizing the GP subject to a total power constraint is solved, a possible approach would be to cut off the sum over μ in (4.18.5) at $\mu = 1$, which results an approximation except for the 4-QAM modulation. The optimal solution can now be obtained in closed form, as shown in [7], but the approximation introduced makes the solution underrate the QoS constraint and thus to allocate less power compared to the optimal solution. In other words, we get a *lower bound* of the optimal solution.
2) In order to circumvent the problem of the underestimation of the QoS constraint, another approximation could be exploited, by still cutting μ at $\mu = 1$, and replacing $\alpha'_{n,1}$ with $\alpha'_{n,1} + \alpha'_{n,2}$. This inequality follows directly by looking at the values assumed by the coefficients α_μ and ψ_μ for a given modulation order [4]. Also in this case we get a closed form solution, which results an upper bound of the optimal solution. The QoS is thus satisfied but with an unecessary waste of power [7].
3) Relying on the above observations, the idea is to find a closed-form solution which lays in the middle between the upper and lower bound solutions.. To this end, let us cut the sum over μ in the QoS constraint of (4.18.5) at $\mu = 1$ and approximate $\alpha'_{n,1}$ as $\alpha'_{n,1} + \delta\alpha'_{n,2}$, where the scalar δ, $0 \le \delta \le 1$, is such that $\sum_{n=1}^{N} p_n^{(o)} = \sum_{n=1}^{N} p_n^*$, being $p^{(o)} = [p_1^{(o)}, \ldots, p_N^{(o)}]^T$ the optimal solution obtained via the numerical method, and $p^* = [p_1^*, \ldots, p_N^*]^T$ is the one obtained solving (4.18.5) with the above approximation on the QoS constraint. In particular, the latter solution has the following closed-form:

$$p_n^* = \rho_n \left[\log \Theta^* - \log \frac{\rho_n}{\bar{\alpha}_n} \right]_0^{\bar{p}_n^{(max)}}, \qquad (4.18.7)$$

being $\bar{\alpha}_n \stackrel{\Delta}{=} \alpha'_{n,1} + \delta\alpha'_{n,2}$ and Θ^* such that $\sum_{n=1}^{N} p_n^* = \kappa$.

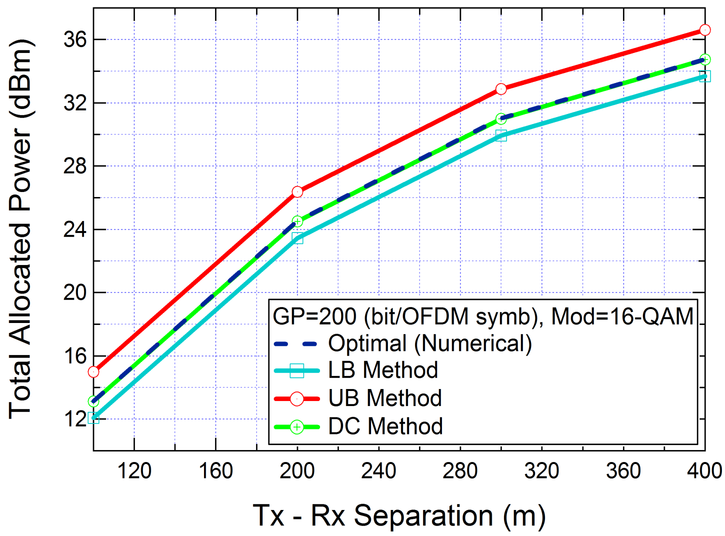

Figure 4-39: Total allocated power by the four PA methods.

Figure 4-39 compare the optimal PA obtained via numerical method with that obtained via the lower bound (LB), upper bound (UB) and delta constraint (DC) methods, over a point-to-point link with 16-QAM, turbo code with rate 1/3, target GP equal to 200 bit/OFDM symbol, as a function of the distance between the transmitted and the receiver.. As expected, the LB method allocates few power, whereas the UB too much. The DC approch instead closely match the optimal solution, but with the advantage of offering a closed-form solution. Moreover, the factor δ can be computed once and stored in a look-up table, since it only depends on the pair modulation order and coding rate.

Game Formulation for the QoS-constrained GPR maximization problem

Assuming that there is no centralized unit, users of different SCs must coordinate among themselves in a distributed manner in order to reach a stable configuration. In particular, we are interested in designing a distributed PA algorithm so that each user maximizes its EE accounting for the interference caused by the users in the other SCs. In particular, given the reference scenario described above, recalling the observations done in the point-to-point case, and rewriting for the sake of notation $\alpha'_{k,q,n,1} + \delta\alpha'_{k,q,n,1}$ as $\alpha_{k,q,n}$, $\bar{p}^{(\max)}_{k,q,n}$ as $\bar{p}_{k,q,n}$, and $\bar{\mathrm{N}}_{k,q}$ as $\mathrm{N}_{k,q}$, the PA problem can be written as[1]

$$\begin{aligned} \min_{\mathbf{0}\le\mathbf{p}_{k,q}\le\bar{\mathbf{p}}_{k,q}} \quad & u_{k,q}(\mathbf{p}_{k,q}) \\ \text{s.t.} \quad & \sum_{n\in\mathrm{N}_{k,q}} \alpha_{k,q,n} e^{-\frac{p_{k,q,n}}{\rho_{k,q,n}(\mathbf{p}_{-q,n})}} \le \kappa_{k,q} \end{aligned} \quad ,\forall k\in\mathrm{K}_q, \forall q\in\mathrm{Q}, \qquad (4.18.8)$$

where $u_{k,q} \triangleq \sum_{n\in\mathrm{N}_{k,q}} p_{k,q,n}$. We can note that (4.18.8) entails a competition for the frequency resources to be used in the uplink between every user and its relevant SBS. This problem can thus be solved by modeling it in the framework of non-cooperative game theory [10], which offers an analytical framework that describes how rational entities interact and make appropriate choices so as to find their own maximum utility. Accordingly, we can introduce the game $\mathrm{G} \triangleq \{\mathrm{K}, \mathrm{P}, \mathrm{U}\}$, described as follows:

1) $\mathrm{K} \triangleq \mathrm{K}_1 \times \cdots \times \mathrm{K}_Q$ is the overall set of users (i.e., players);

2) $\mathrm{P} \triangleq \mathrm{P}_{1,1} \times \cdots \times \mathrm{P}_{K_Q,Q}$ is the set strategies, where the strategy of user k in SC q is its feasible PA set, defined as $\mathrm{P}_{k,q} \triangleq \left\{p_{k,q,n} \mid g_{k,q}(\mathbf{p}_{k,q}, \mathbf{p}_{-q}) \le 0,\ \ 0 \le p_{k,q,n} \le \bar{p}_{k,q,n}, \forall n\in\mathrm{N}_{k,q}\right\}$, $\forall k\in\mathrm{K}_q, \forall q\in\mathrm{Q}$, with $g_{k,q}(\mathbf{p}_{k,q}, \mathbf{p}_{-q}) \triangleq \sum_{n\in\mathrm{N}_{k,q}} \alpha_{k,q,n} e^{-p_{k,q,n}/\rho_{k,q,n}(\mathbf{p}_{-q,n})} - \kappa_{k,q}$;

3) $\mathrm{U} \triangleq \{u_{1,1}, \ldots, u_{K_Q,Q}\}$ is the set collecting the utility functions.

In particular, the QoS constraints introduce an interdependency among the strategies of the players, i.e., $\mathrm{P}_{k,q} = \mathrm{P}_{k,q}(\mathbf{p}_{k,q}, \mathbf{p}_{-q})$. In other words the set of strategies of the generic player k depends on the other players' strategies. The solution of game (4.18.8) is thus investigated in terms of *generalized Nash equilibrium* (GNE), which corresponds to the case where no

[1] In the following expression, the variable $\kappa_{k,q}$ is the same than κ, introduced in eqn. (4.18.5) evaluated for user k in cell q.

player can increase its payoff still satisfying its QoS by changing its strategy given those of others.

Remark 1. One can note that, for a fixed strategy $\mathbf{p}_{-q}$ of the other players, the solution of (4.18.8) corresponds to the point-to-point case. Thus, in this case the solution is unique, and is given by $\mathbf{p}^*_{k,q} = \mathrm{BR}\left(\mathbf{p}_1,\ldots,\mathbf{p}_{q-1},\mathbf{p}_{q+1},\ldots,\mathbf{p}_Q\right)$, where the nth component of the best response (BR) operator is defined as

$$\left[\mathrm{BR}\left(\mathbf{p}_{-q}\right)\right]_n = \rho_{k,q,n}(\mathbf{p}_{-q})\left[\log\Theta^*_{k,q,n} - \log\frac{\rho_{k,q,n}(\mathbf{p}_{-q})}{\alpha_{k,q,n}}\right]^{\bar{p}_{k,q,n}} \tag{4.18.9}$$

and $\Theta^*_{k,q,n}$ is such that the optimal PA $p^*_{k,q}$ satisfies the QoS constraints with equality.

Further, among the vectors $p \in \mathcal{P}$, the vector $p^* \stackrel{\Delta}{=} [p^{*\,\mathrm{T}}_{1,1},\ldots,p^{*\,\mathrm{T}}_{K_Q,Q}]^{\mathrm{T}}$ is a GNE [10] for game $\mathcal{G}$ if $u_{k,q}(\mathbf{p}^*_{k,q}) \le u_{k,q}(\mathbf{p}'_{k,q}),\ \forall \mathbf{p}'_{k,q} \in P_{k,q}(\mathbf{p}^*_{-q}), \forall k \in K_q, \forall q \in Q$.

Thus, according to the definition of GNE and recalling Remark 1, the GNE of the game must satisfy the following condition.

Proposition 1. If problem (4.18.8) is feasible, i.e. if there exist a PA vector $\mathbf{p}^{(\mathrm{f})}$, with elements $0 \le p^{(\mathrm{f})}_{k,q,n} \le \bar{p}_{k,q,n},\ \forall k,q,n$, such that QoS constraints are met with equality, then there exists at least one PA vector $\mathbf{p}^*$ which is a GNE equilibrium of the game. Moreover, such GNE must satisfy the so-called *best response* solution for each user, by solving the fixed-point system of equations $\mathbf{p}^*_{k,q} = \mathrm{BR}\left(\mathbf{p}^*_1,\ldots,\mathbf{p}^*_{q-1},\mathbf{p}^*_{q+1},\ldots,\mathbf{p}^*_Q\right),\ \forall k,q$, with the operator BR defined as in (4.18.9).

Remark 2. The above fixed-point system of equations might lead to more than one solution, especially (and intuitively) when the channel realizations among the users are unbalanced, as usually happens in similar cases [11], [12]. Moreover, the solution of game may not exists, since there may not exist a PA vector $\mathbf{p}^*$ that satisfies all the QoS constraints of all the players in the game at the same time. Thus, before going into details of the proposed distributed PA algorithm to solve (4.18.8), analysis of the existence and uniqueness of the GNE of the game is carried out.

Existence of the GNE. A sufficient condition for the existence of at least a solution for game (4.18.8) is derived in [7] and amounts to show that the matrices $\{\boldsymbol{Z}_n\}$, $\forall n$, depending on the vector of required GP values $\gamma^* = [\gamma^*_{1,1},\ldots,\gamma^*_{K_Q,Q}]^T$ defined in (4.18.6) and the channel coefficients vector (4.18.1), are *P*-matrices. In order to better understand the physical meaning of the existence condition, let us first express the channel coefficient as a function of the path loss (PL) between the relevant transmitter and receiver pair, i.e., $|h_{r,s,q,n}|^2 L_{r,s,q} = |\tilde{h}_{r,s,q,n}|^2$, where $L_{r,s,q}$ is the path loss between between transmitter r in SC s and receiver q and $\tilde{h}_{r,s,q,n} \in \mathcal{CN}(0,1)$. Since a sufficient condition for the matrices $\{\mathbf{Z}_n\}$ to be P-matrices is that they satisfy the diagonal dominance condition, then the existence condition can be further written as

$$\sum_{s\neq q}\sum_{r=1}^{K_s}\frac{|\tilde{h}_{r,s,q,n}|^2}{|\tilde{h}_{k,q,q,n}|^2}\frac{L_{k,q,q}}{L_{r,s,q}} < \frac{\psi_{k,q}}{\gamma^*_{k,q}} \quad \forall n \in \mathcal{N}_{k,q}, \forall k \in \mathcal{K}_q, \forall q \in \mathcal{Q}. \tag{4.18.10}$$

Thus, as early anticipated, the above condition states that as long as the ratio between the interfering channel and the direct one (i.e., that between the transmitter and receiver) is lower than a certain threshold, or, in other words, the interference is small enough, then a solution for game (4.18.8) exists. The threshold depends on the GP constraints, expressed in terms of optimal effective SNR, and the modulation employed by the generic transmitter, via the coefficient $\psi_{k,q}$. Thus, the more distant the competing transmitters, the lower the interference and thus the higher the probability of having a not empty solution set. It is worth noting that this condition is in agreement with that derived in [11] with Gaussian signalling. In fact, ψ can be view as a SNR gap and, in case of Gaussian signalling, $\psi = 1$ and $\gamma^* = e^{R^*} - 1$, where R^* is the desired rate.

Uniqueness of the GNE. [7] also shows how to derive the condition for the uniqueness of the solution of the GNE. As in the existence case, this condition depends on the distance between the interfering users and the on the target QoS.

Distributed PA algorithm.

Since we are dealing with a decentralized implementation, where no signaling among different SCs is allowed, our aim is to derive a totally distributed iterative algorithm. In fact, this allow every user to independently optimize its own PA according to the SINR perceived, which entails the interference caused by the other users. Recalling *Proposition 1*, a natural scheme is that based on the *best response*, where the only available local information $\{\gamma_{k,q,n}\}$ is fed back from SBS q to user k which can compute its PA according to (4.18.9), assuming other players have already played their strategies $\mathbf{p}_{-q}$. This procedure is iterated for all the users until convergence is reached, as described in [7]. Moreover, the best-response based algorithm converges under the same conditions for which the GNE is unique.

Simulation Results

Figure 4-40 depicts the reference scenario. We consider one user per SC and we evaluate the performance of user in SC as a function of the distance between him and its SBS. Each simulated point is obtained averaging over 10^3 channel realizations and the position of every user in the other SCs is randomly chosen at each channel realization. The radius of each SC is 100 m. Every user-SBS link is characterized by the following features: N=1320 subcarriers,

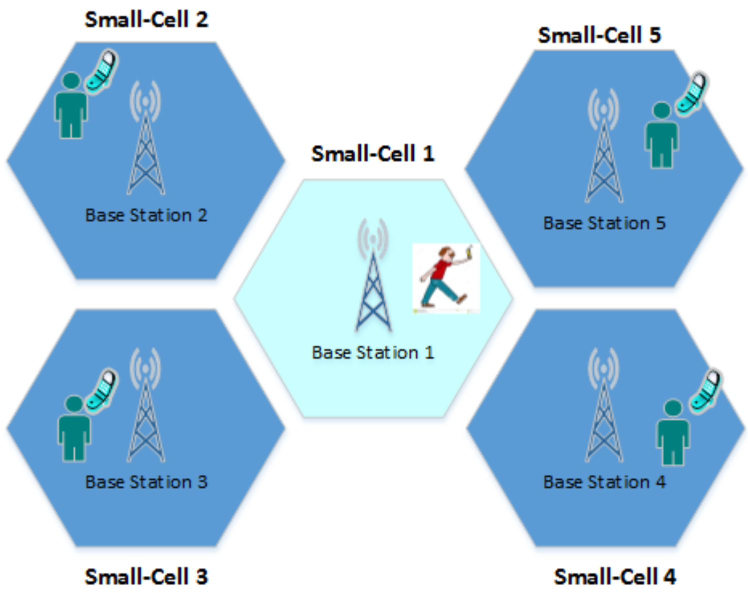

Figure 4-40: Reference simulation scenario.

4-, 16- and 64-QAM as modulation format, channel encoding based on a Turbo Encoder (TC) composed by two parallel convolutional encoder, with mother code rate 1/3 properly punctured to allow the eight rates 1/3, 2/5, 1/2, 4/7, 2/3, 3/4, 4/5 and 6/7, availabe power of 10 dBm, cyclic prefix of length 160 samples, signalling interval equal to 50 ns, corresponding to a bandwidth of 20MHz. Each RLC-PDU consists of a payload of 1024 information bits, preceded by the CRC section of length 32 bits. The channel model is the ITU-Pedestrian B channel.

Figure 4-41 and **Figure 4-42** show the total allocated power (TAP) with the distributed PA algorithm described abover, for two different target values, and the correspondent percentage of number of active subcarriers over the band B assigned at every user. It is well known that the lower the modulation order the higher the power efficiency. Though, as the target GP value becomes higher, the number of active subcarriers per user increases enhancing the multi-user interference (MUI). This leads to an increament of the TAP with the consequence that greater modulation orders, such the 16-QAM, have the same power efficiency of the 4-QAM, since it requires less active subcarriers to satisfy the GP constraints, thus keeping lower the MUI.

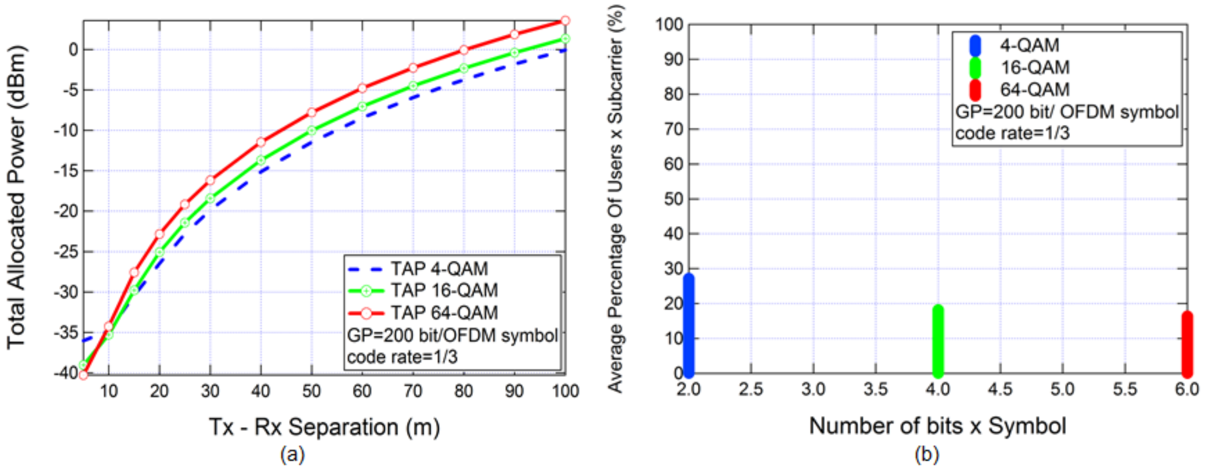

Figure 4-41: TAP with taget GP of 200 bit/OFDM symbol.

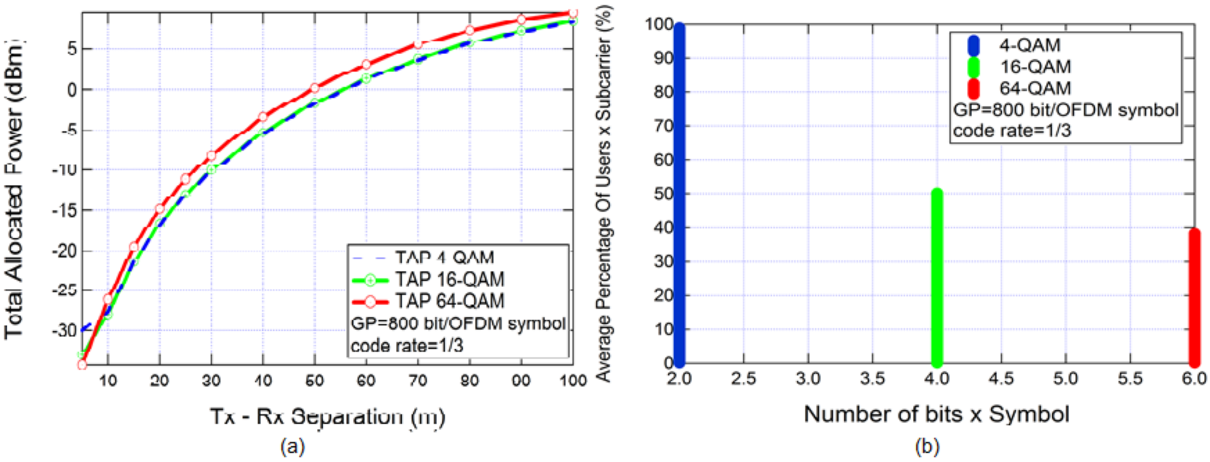

Figure 4-42: TAP with taget GP of 800 bit/OFDM symbol.

4.18.2 References

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4.19 Achievements JRA1.3.3C – Self-configuration and optimization of a hybrid LTE Femto - M2M network

4.19.1 Description

We face in this JRA the challenge of scheduling Machine to Machine (M2M) traffic over a Long Term Evolution (LTE) small cell network densely deployed over the lamp posts of a big boulevard for smart city applications, as is represented in Figure 4-43. In Deliverable D13.1, we have presented the 3rd Generation Partnership Project (3GPP) architecture which supports the proposed scenario and we have discussed the main open research challenges together with the relevant state of the art. We have then proposed to focus on the scheduling of M2M traffic in the uplink of this scenario characterized by high inter-cell interference.

Among the research challenges listed in D13.1, we have proposed to focus on the problem of scheduling both M2M and H2H traffic in the same spectrum. Considering that the current applications for M2M traffic are mainly served through the uplink of the communication network, we focus on this problem, which is also more challenging as cellular networks are mainly designed to transfer the great majority of traffic in downlink.

The first challenge to tackle in the scenario that we have proposed is to efficiently allocate radio resources in order to manage and control the interference that the different small cells can cause to each other in the stressed urban scenario. A huge amount of algorithms have been proposed in literature to solve this problem in small cells and femtocell scenarios, but mainly focusing on the downlink of the cellular network. In this case, the LTE system relies on the Orthogonal Frequency Division Multiple Access (OFDMA) multiple access scheme, which has many benefits for high speed data services. However, one disadvantage is that the instantaneous transmitted Radio Frequency (RF) power can vary significantly within a single Orthogonal Frequency Division Modulation (OFDM) symbol, leading to large Peak to Average Power Ratio (PAPR), which entails a distortion problem in the linear devices. This drawback has a major impact in the uplink, since power consumption is an important consideration for mobile handsets. To address this drawback, SC-FDMA has been adopted. This different access scheme imposes very different constraints, which strongly affect the resource allocation, interference management policy and the scheduling of traffic. In particular, SC-FDMA requires contiguous Resource Block (RB) allocation to the same user. As a result of this constraint, to schedule traffic in the uplink direction in our scenario, we propose a two step approach:

- Each small cell first senses the spectrum available for resource allocation to its users, so as to evaluate the blocks of contiguous RBs, where it measures an acceptable level of interference.

- Based on the availability of contiguous RBs and on the QoS requirements of the traffic to be scheduled by each user, RBs are allocated to them properly.

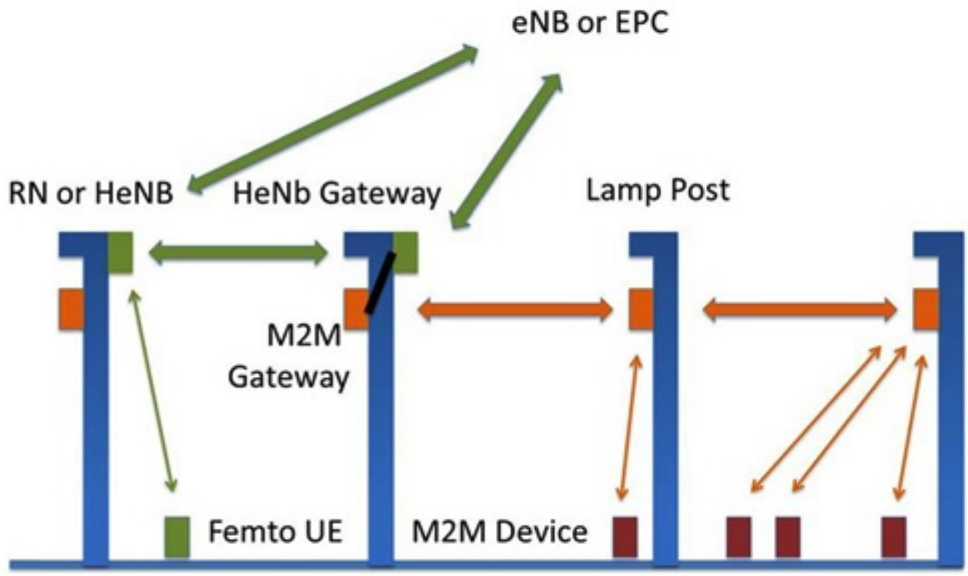

Figure 4-43: High Level scenario

In the first reporting period, we have focused on a preliminary study of the first step of our proposal and evaluated via system level simulations the probabilistic distribution of available contiguous RBs, which can be used for scheduling uplink M2M traffic, when different traffic distributions are served by the small cell network. Simulation results obtained with the support of a LTE Release 10 network simulator implementing two different traffic patterns, show that, taking into account the particular characteristics of M2M traffic, multiple scheduling opportunities are available, despite the high inter-cell interference generated by the densely deployed small cell network.

We implement the proposed smart city scenario on the LENA [1] LTE simulator, based on Network Simulator v.3 (ns3). The proposed scenario emulates a long boulevard in a city. Coverage is guaranteed by an eNodeB, while the high capacity is guaranteed by a dense small cell deployment. As shown in Figure 4-44, the scenario that we have set is a boulevard of 400 meters where lamp posts are 25 meters far from each other. In the figure yellow dots represent the lamp posts where a small cell is not installed, while red dots are lamp posts with small cells. This dense scenario is justified by the expectations on increment of the traffic in the near future in cities [2], and in particular on the numbers presented [3], where it is evaluated that in 2015 in London, to face the expected mobile traffic, there will be the need for about 100 Small Cell (SC) per square kilometer.
We evaluate through simulations the probabilistic distribution of contiguous RBs which are available for allocation of M2M traffic in the uplink of the small cell network, when two different kinds of traffic are being served by the small cell network:
(I) Each M2M device in the network sends a User Datagram Protocol (UDP) packet to a remote server. The distribution of packets in time is constant, each device uses an interarrival time of 10 msec, while the UDP packet size is constant with a payload of 60 Byte.
(II) We consider a saturation traffic, as it is typical in very dense scenarios. Several saturation traffic generators are available in the simulator, one for each QoS class defined in [4]. In our

scenario we consider the traffic generator referred to QoS Class Indicator (QCI) 3, which QCI is typically used for Guaranteed Bit-Rate (GBR) real time gaming services.

Figure 4-45 and Figure 4-46 depict some snapshots of the distribution of available and contiguous RBs for different TTIs (Transmission Time Interval), for traffic pattern (I) and (II), respectively. Different colours are related to different TTIs, and the total number of available RBs for a given TTI is the sum over the bars of the same colours. For instance, for traffic pattern (I) the total number of available RBs for ”green” TTI is 42, while for the TTI ”blue” is 27. Figure 4-47 and Figure 4-48 represent the cumulative probability distribution function (PDF) over the dimension of contiguous and available RBs, for traffic patterns (I) and (II), respectively. The probabilistic behavior is similar for the two traffic patterns, and the most frequent number of contiguous RBs is 3. This is a very convenient number for M2M traffic, which generally is quite low in terms of capacity demand. In addition, we observe the following differences. The number of contiguous RBs in case of traffic pattern II is more spread than the one of traffic pattern I, which is in turn concentrated around smaller values. The reason is that traffic pattern I is characterized by a high number of devices transmitting short messages, and so occupying a reduced number of RBs, which leaves space for a distribution of empty contiguous RBs concentrated in the lower values. On the other hand, traffic pattern II is generated by a lower number of users, but is more demanding in terms of payload, thus the number of RBs needed for transmitting this traffic is more variable and also depends on the used Modulation and Coding scheme, which explains the more spread probability distribution.

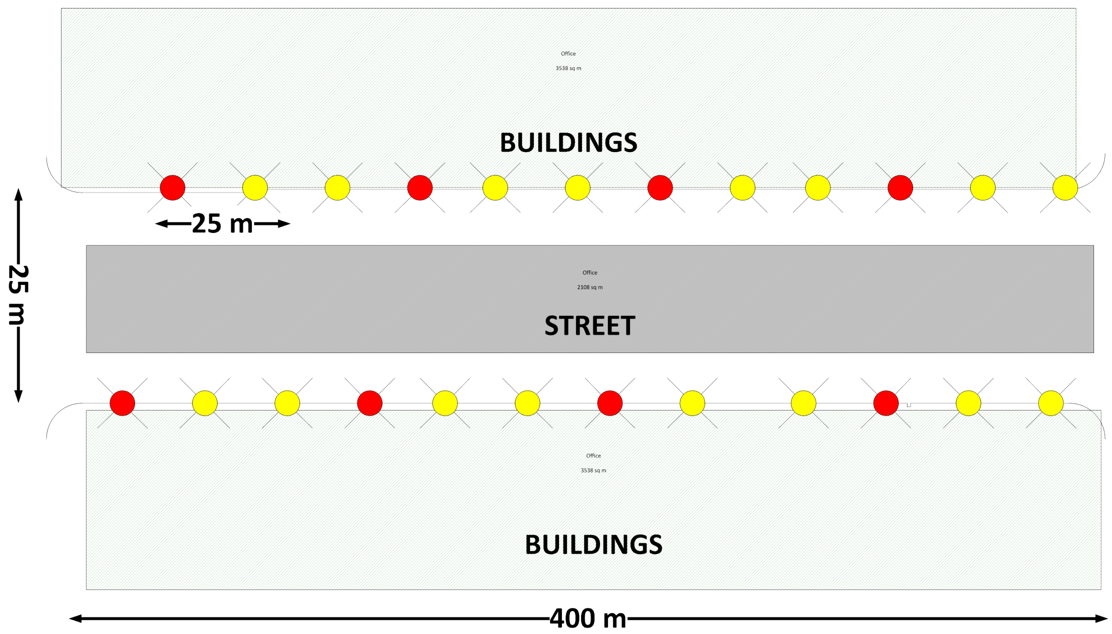

Figure 4-44: - Simulated scenario.

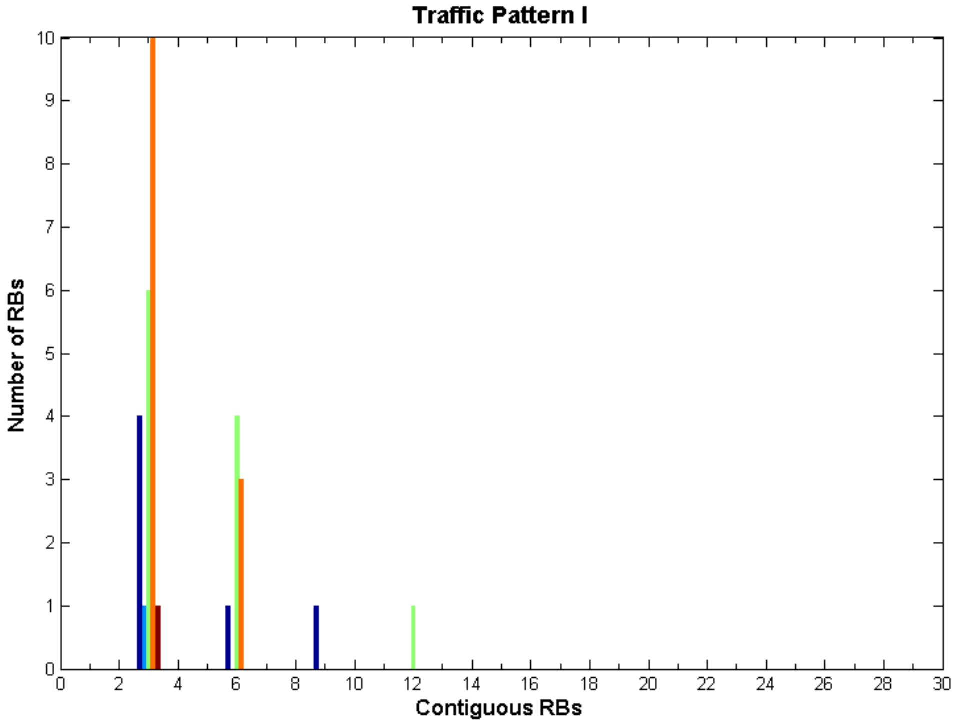

Figure 4-45: Snapshots of available and contiguous RBs for traffic pattern I.

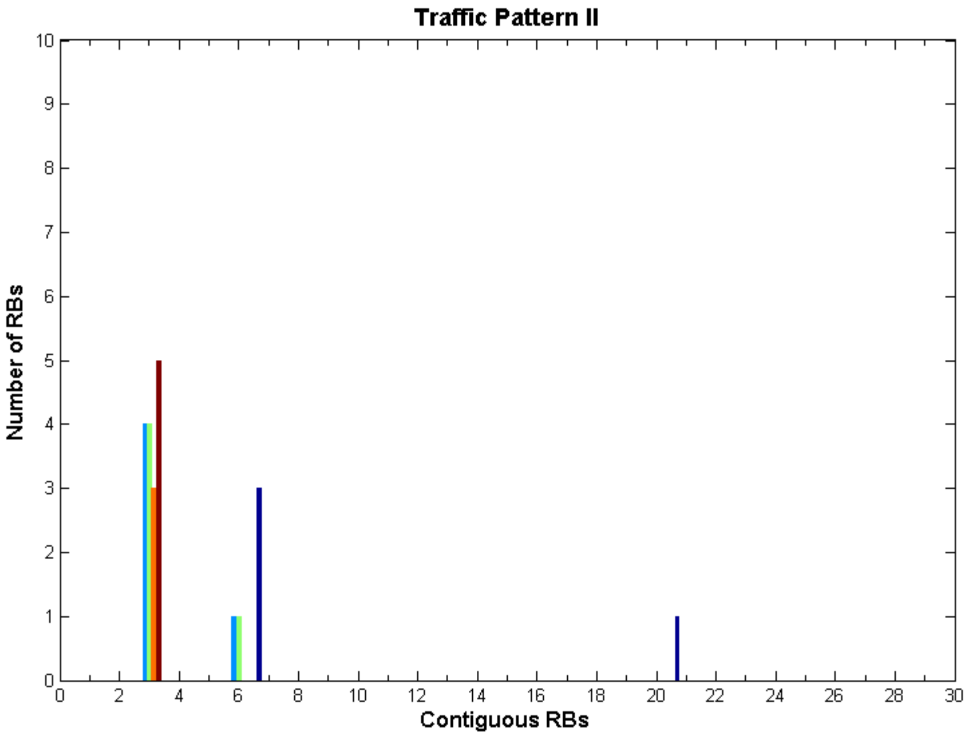

Figure 4-46: Snapshots of available and contiguous RBs for traffic pattern II.

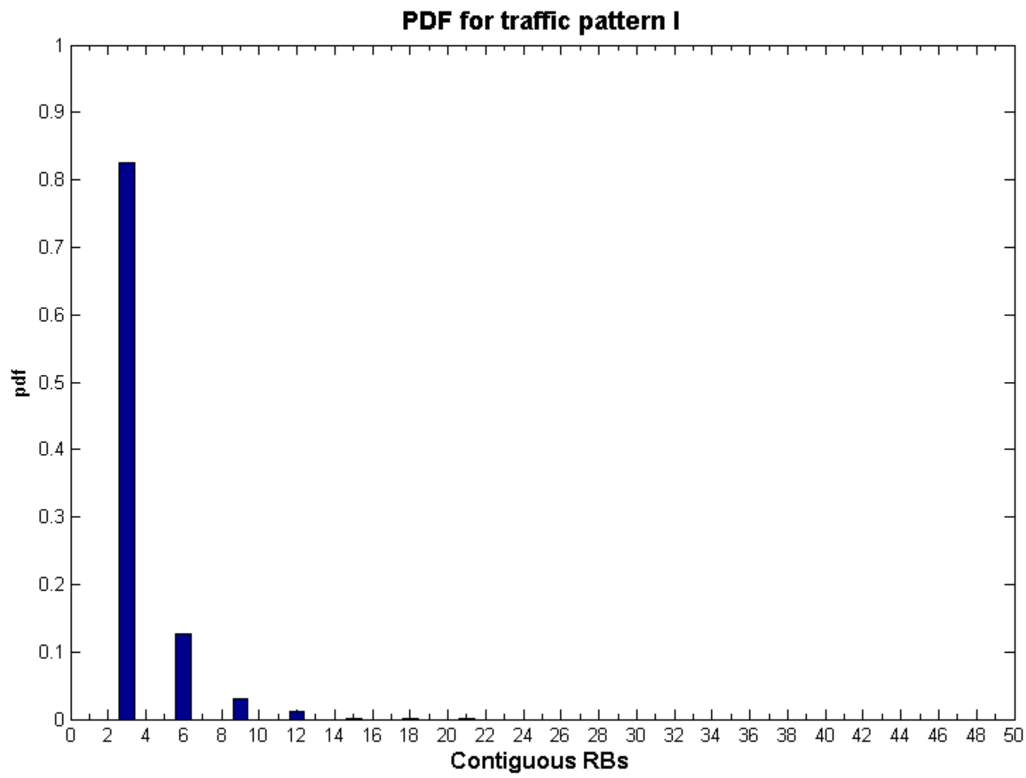

Figure 4-47: Probability distribution of contiguous RBs for traffic pattern I

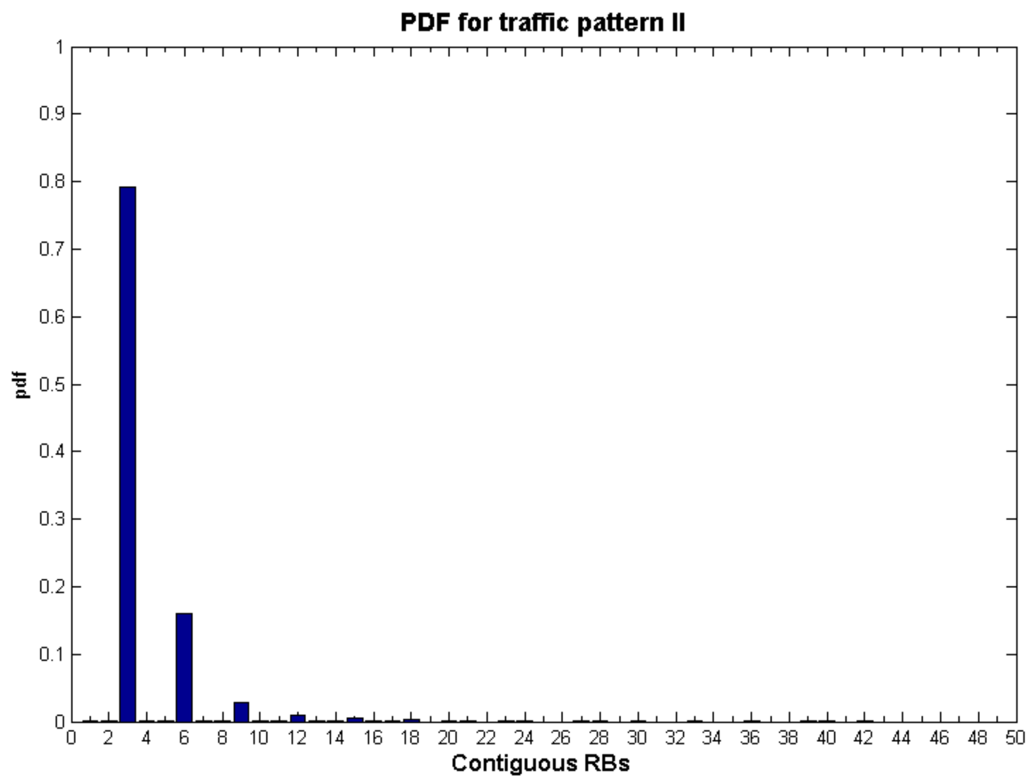

Figure 4-48: Probability distribution of contiguous RBs for traffic pattern II

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4.20 Achievements JRA1.3.3D – Radio resource allocation algorithms in cognitive radio networks with outdated CSI

This section first presents the state of the art of the RA techniques for multicarrier systems and then discusses some of the most interesting results obtained in the framework of the JRA 1.3.3D during the reporting period.

4.20.1 State of the art

OFDM technology is extremely flexible and it is able to adapt to varying channel condition and service requirements. As such, OFDM technology can provide reliable and fast communications satisfying the required QoS with a constrained set of transmission resources over harsh fading channels. This signaling technique can be effectively combined with error correcting codes, exploiting for instance the bit-interleaved coded (BIC) modulation approach [1], that improves code diversity and avoids the need for the complicated and somewhat less flexible design typical of coded modulation. Reliability and efficiency performance can be further boosted by resorting to flexible radio interfaces capable of adjusting their radio resources or transmission parameters (TPs) (e.g. modulation order, coding rate, power) on the fly according to the time-varying conditions of the operating environment, what is known as resource adaptation (RA) [2], [3].

In such a scenario, radio resource management is inexorably plagued, since it would need a reliable (and stable) knowledge of the CSI at the transmitter. As a matter of fact, the transmitter has only an imperfect and/or outdated CSI, which hinders RA and makes performance more and more degraded. On the other hand, a static set-up of the TPs can lead to very poor system performance when the channel conditions are bad or, on the contrary, to a waste of the radio resources when the channel conditions are good. In 3G systems, for instance, dynamic transmit-power control has been used, where the allocated power is dynamically adjusted according to the link quality to guarantee a constant data rate (which is a desirable property for voice services). For packet-data traffic, a more appealing approach consists in simply transmitting at the highest possible rate. This can be obtained by means of dynamic rate control, where the data rate is controlled by adapting the modulation order and the coding rate to the actual channel conditions. Intuitively, the better the channel quality, the higher employed modulation orders and code rates. Such a link adaptation technique is also referred to as adaptive modulation and coding (AMC) [2].

The problem of tackling the outdated CSI is addressed in many works. For instance, in [4], the hybrid automatic repeat request (HARQ) protocol is analyzed for a communication over block-fading channel with fully outdated CSI, while in [5] the impact of outdated CSI is investigated between SUs and PUs in shared spectrum systems. In [5], the effect of feedback delay on RA in an OFDM access system is evaluated. The work in [[8] focuses on adaptive modulation in OFDM systems by considering both perfect and imperfect CSI under a BER constraint, whereas [8] proposes an AMC scheme for a BIC-OFDM system with outdated CSI subject to a BER constraint.

RA strategies usually aim at maximizing the capacity or the mutual information (e.g., see [9] and references therein). Based on this approach, AMC and power allocation (PA) strategies have been studied in [10] and [11] for BIC-OFDM and MIMO-BICM systems, respectively. However, an effective RA strategy should be able to take into account, in a cross-layer manner, not only information on the status of the wireless channel, but also the information coming from the upper layers such as in packet-oriented transmission. As matter of fact, information-theoretic performance limits, which rely on ideal assumptions like Gaussian inputs and infinite length codebooks, can reveal inadequate to give a reliable picture of the actual link performance [12]. To this end, a significative cross-layer optimization criterion is represented by the goodput (GP) [13], [14], [15]. This metric characterizes in more a suitable way the actual performance of a packet-oriented communication system and it is defined as the number of information bits delivered in error-free packets per unit of time. In this context, [16] and [17] adopt the GP as performance metric to select the best combination of modulation and coding rate with uniform bit and power loading. In [13], instead, the GP criterion motivates the problem of optimally distributing bits and power across a set of subchannels in a coded adaptive OFDM system with hard Viterbi decoding. In particular, the hard decisions on the coded binary symbols are exploited so as to split the cross-layer nature of the problem by using the uncoded BER (at the decoder input) as an intermediate performance metric. On the other side, when soft Viterbi decoding is considered this layer separation is not trivial at all. Thus, to make feasible the RA multiparametric optimization problem (OP), the derivation of an accurate link performance prediction (LPP) metric providing a compact and manageable analytic representation of the GP performance is a crucial task. In this sense, one of the most promising LPP method to be mentioned is the effective signal-to-noise ratio (SNR) mapping (ESM) [18], such as the exponential ESM (EESM), logarithmic ESM (LESM), capacity ESM (CESM), and mutual information ESM (MIESM) schemes [19]. In particular, the EESM has the main advantage of providing a closed-form mapping function, but unfortunately, its generalization to high order modulations [20] does not exist. Differently from EESM, the MIESM solution includes two separates models, one for modulation and the other for coding, thereby enabling the separation between layers and making RA very convenient [21], although the mutual information mapping function has not a closed-form expression. Finally, in the literature it is present perhaps the most promising LPP technique that is called κ ESM and was originally proposed in [15]. This LPP allows getting an estimate of the GP, referred to as expected GP (EGP), which represents the objective function of the RA problem in order to get an accurate performance prediction. Moreover, the RA problem is able to perform AMC and PA strategy in two separated steps by maximizing the EGP function.

4.20.2 RA Techniques in CR BIC-OFDM systems with DF Relay and Imperfect CSI

The research activity carried out wthin the JRA deals with RA techniques for CR BIC-OFDM systems, with DF relay nodes, in the presence of outdated and imperfect CSI. The aim is maximizing the GP metric over the available radio resources: power distribution on the subchannels, coding rate and modulation order. The GP metric is a significant figure of metric that is used to select the best combination of modulation, coding rate and an optimal distribution of the available power. Moreover, GP quantifies the trade-off between data rate and link reliability and it is more suitable metric to quantify the actual performance of packet-oriented systems employing practical modulation and coding schemes.

The goals of the research are:

1. Derivation of a RA technique that assigns modulation, coding rate and power for CR OFDM systems employing bit-interleaved coded modulation (BICM) with outdated and imperfect CSI;
2. Exstension of the scenario of the previous point considering a generic number of decode-and-forward (DF) relay nodes (RNs) for a dual-hop transmission (source-

relay-destination). Therefore, a “best relay” selection mechanism will be considered exploiting the GP metric;

3. Improvement of the RA technique in a more realistic scenario, where only imperfect CSI is available to the transmitter for a multi-hop transmission. Then, a “best path” selection will be derived exploiting the GP metric.

Delving into more details, given an OFDM transmission system N subcarriers, the aim of the RA problem is to find the optimal transmission mode (TM) $\varphi^* \triangleq \{\mathbf{m}^*, r^*\}$ that is the optimal number of bits per subcarrier $\mathbf{m}^* \triangleq [m_1^*, \cdots, m_N^*]^{\mathrm{T}}$, the optimal coding rate r^*, and the optimal power allocation (PA) vector $\mathbf{p}^* \triangleq [p_1^*, \cdots, p_N^*]^{\mathrm{T}}$, that maximizes the system goodput. So, a robust and spectrally efficient multicarrier transmission over time-frequency selective channels can be obtained. Towards this end, we need to resort to a link performance prediction (LPP) model that allows to derive an estimate of the goodput, i.e., the EGP, which represents the objective function of the RA problem over which the above-mentioned transmission parameters are optimized. The major challenge consists in obtaining an accurate prediction of the packet error rate (PER) (on which the goodput depends) for coded OFDM systems. An effective solution is offered by the κ ESM method, originally proposed in [15]. The key idea is to compress the vector of the received SNRs $\Gamma \triangleq [\gamma_1, \cdots, \gamma_N]^{\mathrm{T}}$, which represents the CSI, into a single SNR value γ_{eff}, called effective SNR, which is used to estimate the PER for an equivalent binary coded system with code rate r operating over an AWGN channel, so that

$$\mathrm{PER}_{\mathrm{AWGN},\, r}\left(\gamma_{\mathrm{eff}}\right) = \mathrm{PER}_{\mathrm{BIC\text{-}OFDM},\, r}\left(\Gamma\right) \tag{4.20.1}$$

According to [15], γ_{eff} can be evaluated as

$$\gamma_{\mathrm{eff}} \triangleq -\log\left[\frac{1}{\sum_{j=1}^{N} m_j} \cdot \sum_{n=1}^{N} \alpha_n \cdot \mathrm{e}^{-p_n \gamma_n \beta_n}\right] \tag{4.20.2}$$

where α_n and β_n are constant values depending on m_n. Therefore, the EGP expression, expressed in (bit/s/Hz), results

$$\zeta\left(\varphi, \mathbf{p}\right) \triangleq \zeta_0 r \sum_{n=1}^{N} m_n \left\{1 - \mathrm{PER}_{\mathrm{AWGN},\, r}\left[\gamma_{\mathrm{eff}}\left(\mathbf{m}, \mathbf{p}\right)\right]\right\} \tag{4.20.3}$$

where ζ_0 is a constant value.

The RA problem was formulated as

$$
\begin{aligned}
&\left(\varphi^{*},\mathbf{p}^{*}\right)=\underset{\varphi,\mathbf{p}}{\operatorname{argmax}}\left\{\zeta\left(\varphi,\mathbf{p}\right)\right\}\\
\text{s.t.}\quad &\sum_{n=1}^{N}p_n\le N\\
&\varphi\in\Phi
\end{aligned}
\tag{4.20.4}
$$

where $\Phi\triangleq\mathcal{D}_{\mathrm{m}}\times\mathcal{D}_{\mathrm{r}}$ is the set of feasible TMs. Given the specific structure of the objective function $\zeta(\varphi,\mathbf{p})$, the problem is solved by splitting it into two consecutive steps:

1. the optimal PA vector $\mathbf{p}^{*}$ is derived as a function of the generic TM φ;
2. the best pair $(\varphi^{*},\mathbf{p}^{*})$ is selected so that the EGP metric is maximized.

The first step in the JRA was the development of a new LPP model that considers the outdated CSI problem. This work is presented in [22]. In detail, the proposed LPP model is developed starting from the outdated channel model for the generic subcarrier n

$$\breve{H}_n\triangleq\rho\bar{H}_n+\sqrt{1-\rho^2}\,v_n \tag{4.20.5}$$

where $\breve{H}_n$ models the predicted channel coefficient, $\bar{H}_n$ is the outdated channel coefficient obtained by channel estimation at the receiver, ρ is the channel correlation coefficient depending on the delay time on the feedback channel and to the relative speed between transmitter and receiver. The expression of this model called imperfect-channel κ ESM (IC-κ ESM) is

$$\breve{\gamma}_{\text{eff}}\triangleq-\log\left[\frac{1}{\sum_{j=1}^{N}m_j}\cdot\sum_{n=1}^{N}\breve{\alpha}_n(\rho)\cdot\mathrm{e}^{-p_n\gamma_n\breve{\beta}_n(\rho)}\right] \tag{4.20.6}$$

We note that the only difference w.r.t. the customary κ ESM model γ_{eff} in (4.20.2) is that α_n and β_n have been replaced by $\breve{\alpha}_n$ and $\breve{\beta}_n$ [15], respectively, and consequently the RA algorithm remains the one previously illustrated.

The next step was to further improve the LPP model IC-κ ESM in order to take intop account the presence of imperfect CSI. To this aim, a new channel model was exploited [23], that is shown below for the generic subcarrier n

$$H_n(i)\triangleq\hat{H}_n(i)+e_n(i) \tag{4.20.7}$$

where $H_n(i)$ is the actual channel, $\hat{H}_n(i)$ is the predicted channel, $e_n(i)\in\mathrm{CN}\left(0,\sigma_n^2\right)$ and i is the index of the OFDM symbol. The predicted channel $\hat{H}_n(i)$ is evaluated at the receiver from P previously received channel coefficients, one every D OFDM symbols.

The expression of the new LPP model IC-κ ESM is the same as (4.20.2), where the only differences are α_n and β_n , which are now replaced by

$$\hat{\alpha}_n \triangleq \frac{\alpha_n}{1+\theta^2\sigma_n^2\beta_n} \tag{4.20.8}$$

$$\hat{\beta}_n \triangleq \frac{\beta_n}{1+\theta^2\sigma_n^2\beta_n} \tag{4.20.9}$$

where $\theta^2 \triangleq \frac{S}{\Xi\sigma^2}$, S is the average allocated power, Ξ is the path loss and σ^2 is the variance of the ambient noise. Also the RA method presented in (4.20.4) remains the same.

From this point forward, we are going to test the new model IC-κ ESM by considering a cooperative network in a cognitive scenario as shown in Fig. 4.49. The cooperative network is the network of the SUs that occupies the same bandwidth as a PUs network. This cooperative network consists of a source node (SN), a destination node (DN) and M relay nodes (RNs). We assume that there is no direct link present between the SN and DN. The decode-and-forward (DF) protocol is used at the relays. The transmission of a frame occurs in 2 time slots. In the first time slot the SN transmits a frame consisting of several OFDM symbols to the different RNs. Only the selected RN decodes the received message, which is then re-encoded and forwarded to the DN. The message received at a RN over a particular subcarrier n is forwarded over a subcarrier k, which might be different from n .

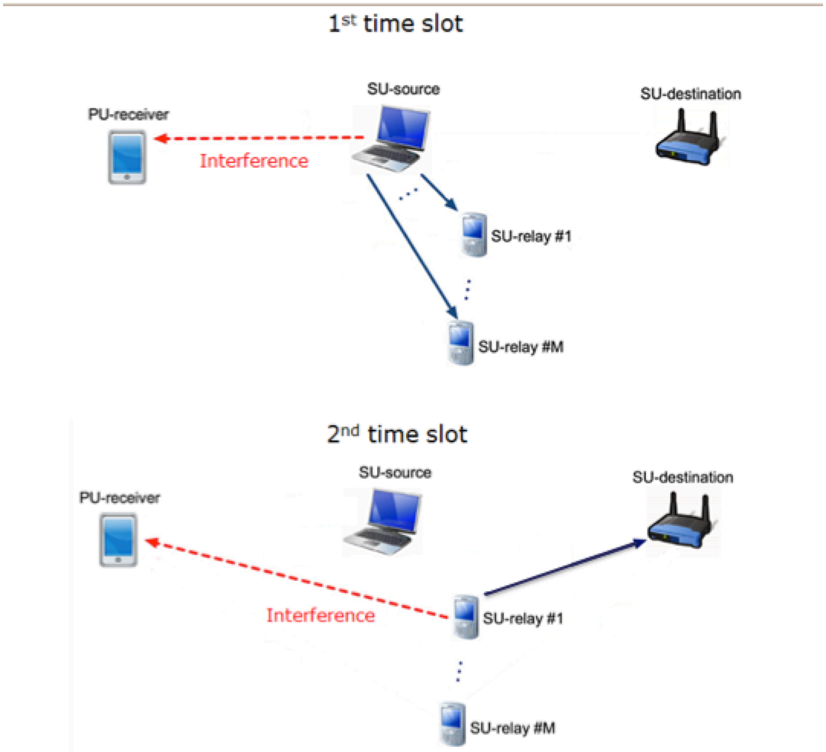

Figure 4.49: System Model.

In the first set of simulations, we will consider only the presence of one DF-RN; at a later stage, a generic number of RNs will be implemented. Then, a best relay selection criterio should be developed exploiting the GP metric.

In a CR scenario the RA problem is different from (4.20.4), because new constraints are now present so as protect the transmissions between the PUs from the interference arising from the SUs. For the moment, we decided to use the PER metric as the objective function. Considering a transmission exploiting a dual-hop DF relay, SN-RN link and RN-DN link are independent each other, thereby the total PER at the DN can be written as

$$PER_{AWGN}^{s,r,d}(r_1, r_2, \hat{\gamma}_{1,eff}, \hat{\gamma}_{2,eff}) = PER_{AWGN}(r_1, \hat{\gamma}_{1,eff}) + (1 - PER_{AWGN}(r_1, \hat{\gamma}_{1,eff}))PER_{AWGN}(r_2, \hat{\gamma}_{2,eff}) \tag{4.20.10}$$

where the index (1) denotes the SN-RN link, the index (2) the RN-DN and $\hat{\gamma}_{\cdot,eff}$ is the effective SNR calculated with the new IC-κ ESMfor the imperfect CSI link.

The RA problem was formulated for the generic link $i \in \mathcal{I} \triangleq \{1,2\}$ as

$$\mathbf{p}^* = \underset{\mathbf{m}^{(i)},\mathbf{p}^{(i)}}{\operatorname{argmin}} \left\{ \mathrm{PER}_{r_i}^{(i)} \right\} \tag{4.20.11}$$

$$\text{s.t.} \quad p_n^{(i)} \geq 0, \qquad \forall n \in N$$

$$\sum_{n=1}^{N} p_n^{(i)} \leq N$$

$$\sum_{n=1}^{N} I_n^{(i)}(q) \leq \Gamma_q^{(i)}, \qquad \forall q \in Q$$

Where $I_n^{(i)}(q)$ is the average interference from the generic secondary transmitter to the PU q over the subcarrier n and $\Gamma_q^{(i)}$ is the interference threshold.

4.20.3 Main Results

First, we present some numerical results of the RA technique for a direct link SN-DN in presence of outdated CSI, to demonstrate the effectiveness of the RA technique exploiting the IC-κ ESM model (4.20.6), compared with the κ ESM (4.20.2). The Figure presents both the analyticaly-evaluted EGP and the actual GP (AGP), which is experimentally evaluted by simulation by averaging the number of information bits delivered in error-free packets per unit of time. The RA based on the κ ESM model gives an optimistic EGP (dotted line with empty circles). Due to the channel variation, indeed, when the transmission is performed with the parameters chosen without caring of the outdated CSI, the AGP (solid line with full circles) turns out far from the expected one. Conversely, the IC-κ ESM model takes into account the outdated CSI at the transmitter, and the results are:

1. the EGP and AGP curves of the IC-κ ESM model (dotted line with empty triangles and solid line with full triangles, respectively) are closer to each other;
2. the AGP based on the IC-κ ESM model outperforms the one based on the κ ESM model.

Figure 4.51 depicts the AGP as a function of ρ, for both κ ESM-based and IC-κ ESM-based RA algorithms, at three SNR values, namely $E_S / N_0 = 4,\ 12,\ 20$ dB, and adopting the ITU Vehicular B channel model. It is apparent that IC-κ ESM reveals accurate for any ρ value, thus outperforming the conventional kESM.

A set of simulations is currently running for deriving the GP performance using the modified IC-κ ESM model considering the channel model (4.20.7), in order to take into account the imperfect CSI in a dual-hop SN-RN-DN. These results will be presented in a paper to be submitted to ICC 2015 conference. The next step of the activity will consist in the extension of the scenario to a multi-hop case.

Finally, a final result is presented to demonstrate how the channel model (4.20.7) is able to predict the actual channel. It shows the rate R (bits/OFDM symbol) as function of the SNR $E_S / N_0(\text{dB})$, in a CR dual-hop link with only a PU, for $\Gamma / \sigma_w^2 = 0,\ 10,\ \infty$ (dB) where Γ is the interference threshold and σ_w^2 is the variance of the ambient noise. Γ has a considerable impact on the performance of the seconary user network for high values of the SNR. For $\Gamma / \sigma_w^2 = 0$ and $= 10$ we clearly notice a limiting value of the rate R with increasing SNR. We have also illustrated the effect of the memory P of the predictor. When $P = 1$ we notice that the SU suffers a considerable performance loss compared to the case with perfect CSI. However, when a predictor with memory $P = 4$ is used, we already notice a considerable performance improvement. By using a larger predictor memory we get a better estimate of the actual channel gains and the resulting performance loss because of imperfect CSI is reduced. If we further increase the predictor memory P from 4 to 7, we notice that the performance improvement becomes negligible.

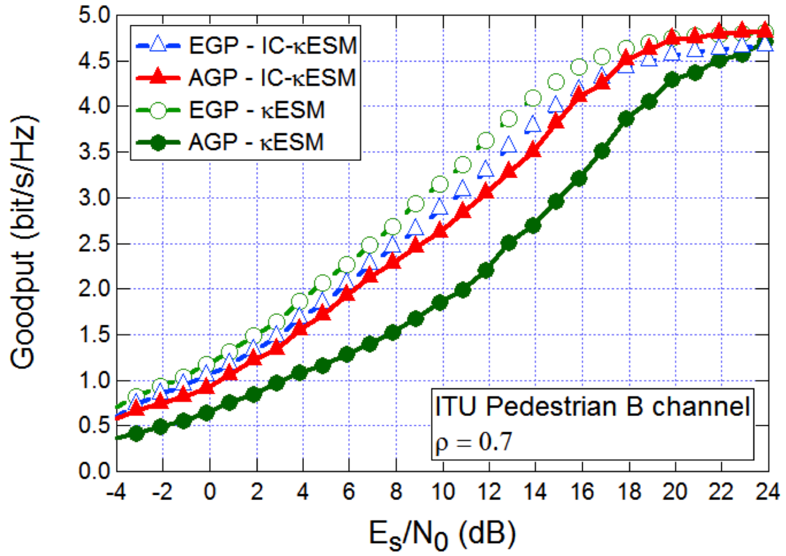

Figure 4.50: GP curves with κ ESM **and** IC-κ ESM.

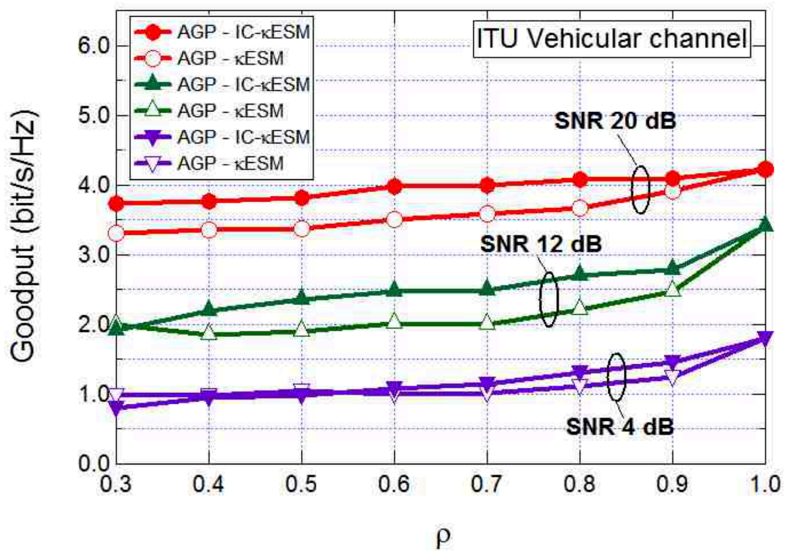

Figure 4.51: AGP curves vs. ρ **with with** κ ESM **and** IC-κ ESM**, for various SNRs.**

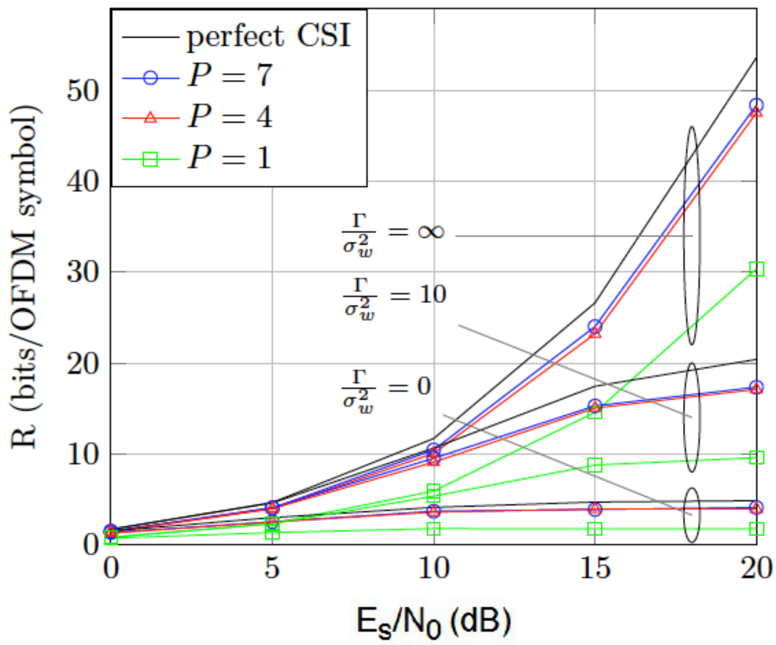

Figure 4.52

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