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Abstract:	The report presents the current status in the research area of energy- and bandwidth-efficient communications and networking and highlights the fundamental issues still open for further investigation. Furthermore, the report presents the Joint Research Activities (JRAs) which will be performed within WP1.3. For each activity there is the description, the identification of the adherence with the identified fundamental open issues, a presentation of the initial results, and a roadmap for the planned joint research work in each topic.
Keywords:	energy-, bandwidth-, power-efficiency, resource allocation, interference management, HetNets

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Executive Summary

WP3 targets the investigation of bandwidth and energy efficiency techniques at various levels of current and emerging wireless systems and networks. Research over the last years has focused on improving the spectral efficiency of wireless communications, so that higher data rates can be achieved within a given bandwidth. In order to more often allow the reuse of spectrum, a complementary approach is to add more antennas and devices in order to reduce the distance between the transmitter and the receiver. The combined proliferation of services and hardware infrastructure has led to increased energy requirements for all the network elements, making a necessity for the research community to investigate new techniques for power- and energy- efficient networks and nodes.

As described in the project's Description of Work, 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 Heterogeneous Networks (HetNets).

The deliverable reviews the State of the Art (SoA) in these thematic areas and highlights the fundamental open issues for further investigation.

For each Task, specific JRAs were created that target to address some of the fundamental open issues in the respecting thematic areas. In order to avoid overlap between the various efforts and to enhance cooperation between partners a research harmonization and consolidation procedure was followed. From more than 20 initial proposals, the consolidation procedure resulted in the following 9 JRAs:

Task 1.3.1:
- JRA on Resource allocation and scheduling strategies for energy harvesting devices
- JRA on Energy-efficient data collection and estimation in wireless sensor networks
- JRA on Joint Protocol channel decoding (JPCD)
- JRA on Energy efficient probing in CSMA based multi-rate ad hoc networks

Task 1.3.2:
- JRA on Advanced MIMO techniques (virtual MIMO, MIMO-FBMC) for low-interference transmission
- JRA on Advanced filtering and adaptive signal processing (OOB, PAPR, SIC)

Task 1.3.3:
- JRA on Interference management techniques for heterogeneous networks
- JRA on Game-theoretic energy-efficient control and resource allocation algorithms in heterogeneous networks
- JRA on Self-configuration and Optimization of a Hybrid LTE Femto - M2M Network for Smart City Applications

For each activity there is the description, the identification of the adherence and relevance with the identified fundamental open issues, and a short presentation of the initial output/results. Furthermore, there is a final subsection which summarises the main achievements and present a roadmap for the future joint research work.

Table of Contents

1.Introduction

In the last two decades, the amount and diversity of services provided by wireless systems has been drastically transformed, from limited voice and simple data services to a wide variety of multimedia-data services. This has led to a rapid increase in data-rate requirements within the standards of new and upcoming wireless communication systems. In order to increase the data rates offered, the most straightforward approach is to increase the allocated bandwidth. However, the proliferation of applications that use the air interface as the transmission medium limits the amount of available bandwidth in the radio-frequency spectrum, making it a very scarce and costly resource. Research over the last years has focused on improving the spectral efficiency of wireless communications, so that higher data rates can be achieved within a given bandwidth. A complementary approach is *hardware proliferation*: add more antennas and devices in order to reduce the distance between the transmitter and the receiver, thus allowing the reuse of spectrum. A dense Heterogeneous Network (HetNet) with the deployment of a variety of small cells in a cellular infrastructure is one manifestation of that approach. This combined proliferation of services and hardware infrastructure has led to increased energy requirements for all the network elements, making a necessity for the research community to investigate new techniques for power- and energy-efficient networks and nodes.

The role of this WP is to investigate and propose techniques at various levels of such systems and networks that will increase efficiency in terms of energy and resources. 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.

For each Task specific Joint Research Activities (JRA) were created that target to address some of the fundamental open issues in the respecting thematic areas. In order to avoid overlap between the various efforts and to enhance cooperation between partners, a research harmonization procedure was followed. The partners proposed topics for investigation in a common format, which included a SWOT (Strengths Weaknesses Opportunities Threats) analysis for each topic. More than 20 proposals were collected and after a consolidation procedure the final 9 JRAs were decided. The selected JRAs, and the related cooperation activities along with a detailed description of the initial results and the main achievements are presented in section 3.

This deliverable reviews the State of the Art (SoA) in the abovementioned thematic areas, highlights the fundamental issues, and presents the specific Joint Research Activities (JRAs) which are currently active within the WP. More specifically, in section 2 a literature review is performed for the related research areas. The scope is to identify the fundamental open problems in each thematic area. Because a full review of the SoA in the whole area of energy- and bandwidth-efficient communications and networking is well beyond the scope of this deliverable, the structure and content of section 2 is based on the Tasks and JRAs categorization. Finally, in section 3, the JRAs are presented in a clear and homogeneous way. For each activity there is the description, the identification of the adherence and relevance with the identified fundamental open issues of section 2, a short presentation of the initial output/results, and a roadmap for the joint research work in the following years.

1.1 Glossary

3GPP	3rd Generation Partnership Project
ABC	Access Barring Check
ABS	Almost Blank Subframe
ACE	Active Constellation Extension
APL	Application Layer
ARQ	Automatic Repeat reQuest
ASA	Authorized Share Access
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BICM	Bit interleaved coded modulation
BIM	Background Interference Matrix
BPSK	Binary Phase Shift Keying
CBS	Cell Selection Bias
CC	Cancellation Carriers
CDMA	Code division multiple access
CEPT's	Commission of European Post and Telecommunications
COGEU	COGnitive radio systems for efficient sharing of TVWS in European context
CP	Cyclic Prefix
CRE	Cell Range Expansion
CSG	Closed Subscriber Group
CSI	Channel State Information
CSMA	Carrier-Sense Multiple Access
DL	Downlink
DS	Direct Sequence
ECC	Error-Correcting Codes
EDGE	Enhanced Data rates for GSM Evolution
EE	Energy-Efficiency
eICIC	Enhanced Inter-Cell Interference Coordination
EXALTED	Expanding LTE for Devices
FBMC	Filter-Bank based MultiCarrier
FCC	Federal Communications Commission
FFR	Fractional Frequency Reuse
FSR	Frame Success Rate
GBSC	Geometrically Base Statistical Channel
GMC	Generalized MultiCarrier
GPR	Goodput-to-Power Ratio
H2H	Human-to-Human
HetNet	Heterogeneous Networks
HPA	High Power Amplifier
HSPA	High-Speed Packet Access
ICI	Inter-Cell Interference
ICIC	Inter-Cell Interference Coordination
IHO	Intra-cell Handover
IMD	InterModulation Distortions
JPCD	Joint Protocol-Channel Decoding
JRA	Joint Research Activity
JSCD	Joint Source Channel Decoding
KKT	Karush-Khun-Tucker
LPN	Low Power Nodes
LRA	Link Resource Adaptation

LSA	Licensed Shared Access
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAC	Multiple Access Channel
MCM	MultiCarrier Modulations
MFSK	Multiple Frequency Shift Keying
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MPC	Multi-Path Components
MR	Measurement Report
MRC	Maximum Ratio Combing
MTC	Machine Type Communication
NC-OFDM	Non-Contiguous OFDM
NE	Nash Equilibrium
OAM	Operation, Administration and Maintenance
Ofcom	Office of Communication
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Acess
OOB	Out-Of-Band
OQAM	Offset Quadrature Amplitude Modulation
OSFFR	Optimal static FFR
OSG	Open Subscriber Group
PA	Power Allocation
PAPR	Peak-to-Average-Power Ratio
PC	Power Control
PCC	Primary Component Carriers
PDSCH	Physical Downlink Shared CHannel
PFR	Partial Frequency Reuse
PRC	Peak Reducing Carriers
PSD	Power Spectral Density
PSR	Packet Success Rate
PTS	Partial Transmit Sequence
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QVI	Quasi-Variational Inequality
RA	Random access
RA	Resource Allocation
RACH	Random Access Channel
RB	Resource Block
REM	Radio Environmental Map
RF	Radio Frequency
ROHC	Robust Header Compression
RRAT	Radio resource allocation table
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RX	Receiver
SBCQ	Sequentially Bounded Constraint Qualification
SBS	Small Base Stations
SC	Small Cell
SCC	Secondary Component Carriers
SCN	Small Cell Network

SE	Spectrum Engineering
SFR	Soft Frequency Reuseand
SIC	Successive Interference Cancellation
SINR	Signal to Interference Noise Ratio
SISO	Soft Input Soft Output
SLM	Selective Mapping
SSS	Subcarrier Spectrum Sidelobes
SU	Secondary User
TR	Tone Reservation
TR	Transmission Resource
TVWS	TV White Spaces
TX	Transmitter
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VI	Variational Inequality
WBAN	Wireless Body Area Network
WEHS	Wireless Energy Harvesting Sensors
WiFi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WSDs	White Space Devices

2. State of the Art

This section includes a literature review in the thematic areas of WP1.3 and the identification of the related fundamental open issues. Because a full review of the SoA in the whole area of energy- and bandwidth-efficient communications and networking is well beyond the scope of this deliverable, the structure and the content of this section is based on the Tasks and JRAs categorization.

2.1 Techniques for power-efficient communications

Energy efficient information processing has become a major research problem in mobile wireless communications networks. Mobile communication devices are mainly limited by battery capacities. It is envisioned that the green wireless networks of the future in order to increase their communication efficiency and lifetime will require more energy efficient information processing techniques for acquisition, processing and distribution of information. In the following subsections the main challenges and possibilities for energy efficient communication are presented, together with the study of several energy efficient techniques and algorithm from the terminals' or from a network's point of view. The main current trends on this filed are also discussed, including the use of energy harvesting devices, the design of energy efficient protocols, and network power optimization algorithms.

2.1.1 Resource allocation and scheduling strategies for energy harvesting devices

Energy harvesting, which is known as the process of collecting energy from the environment by different means (e.g. solar cells, piezoelectric generators, etc.), has become a potential technology to charge batteries and, therefore, expand the lifetime of battery powered devices.

In general, the energy harvesting process is modeled as a set of energy packets arriving to the node at different time instants and with different amounts of energy. There exist two well established approaches for the design of optimal transmission strategies, namely, online and offline. The online approach assumes that the node only has some statistical knowledge of the dynamics of the energy harvesting process, which can be realistic in practice; however, there is a lack of realistic models of the energy harvesting profile. The offline approach assumes that the node has full knowledge of the amount and arrival time of each energy packet, which is a feasible situation with controllable energy sources but it is an idealistic situation when the node uses non-controllable energy sources. In any case, the offline approach provides analytical and intuitive solutions and an upper bound on the performance of the different online algorithms. Therefore, the derivation of the optimal offline solution is a good first step to gain insight for the later design of the online transmission strategy of nodes with non-controllable sources of energy.

Using this model for the energy harvesting process, references 5 - [7] derived the optimal resource allocation in different scenarios. The authors of 5 considered dynamic data packet arrivals and found the transmission strategy that minimizes the delivery time of all data packets; however, the authors of 5 assumed an infinite battery capacity. In [2], a node with finite battery capacity was studied, considering that all the data packets are available from the beginning of the transmission. The authors of [3] and [4] found the power allocation strategy, named Directional Water-Filling, that maximizes the total throughput of a wireless energy harvesting sensors (WEHS) operating in a point-to-point link. The minimization of the transmission completion time for a WEHS operating in a broadcast link was considered in [6], [7]. The capacity region of a Gaussian multiple access channel was considered in [8]. Authors in [9] proposed the power allocation strategy that minimizes the transmission completion time for multiple access channels. Two-hop communications where considered in [10] and [11].

In the above the transmitter is considered a battery-limited node with energy harvesting capabilities. For multi-user scenarios where the receivers are nodes with battery limitations, there is still not much literature regarding resource allocation policies. In the following we present the first references on energy efficient resource allocation, though none of them have taken into account the information of the battery level of the terminal. In [13], authors developed strategies to optimize the modulation type based on a global energy minimization while satisfying given throughput and delay requirements. In [14], authors presented a joint design of the physical, MAC, and routing layers to minimize network energy consumption. However, most of previous works are based on the quotient metric of bits per Joule that was firstly introduced by Verdú in [15]. For example, Miao et al. developed resource allocation strategies based on this quotient (e.g. [16]). The main problem associated with this approach is that, even if such quotient is maximized, the data rate obtained by the optimization problem can be very small and not enough for some applications. In addition, these works do not take into account the current battery status in the proposed strategies.

Ambient radio frequency (RF) signals can also 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 [17]. In that sense, it is important to emphasize that the newer applications require higher data rates and that this implies that more capacity efficient network deployments should be considered. Up to now, this increase in capacity efficiency has been shown to be achieved through the deployment of short-distance networks (e.g. femtocells [18]). 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 [19]. He showed that, for the single-antenna additive white Gaussian noise (AWGN) channel there is a nontrivial trade-off in maximizing the data rate versus the power transmission. Later, in [20], authors extended the previous work considering frequency- selective single-antenna AWGN channels. In [21] (and its journal version [22]), 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 which were able to combine both sources (information and energy) at the same time. In [23], authors introduced time scheduling between information and energy transfer and derived the optimal switching policy with time-varying co-channel interference. The receiver, thus, replenished energy opportunistically via wireless power transfer from the unintended interference and/or the intended signal sent by the transmitter. There is another extension that considers the case of wireless information and power transfer with imperfect channel state information (CSI) [24]. In that work, authors proposed a robust beamforming design policy in the same scenario as in [21], but considering imperfection in the channel knowledge.

2.1.2 Energy-efficient data collection and estimation in wireless sensor networks

A sensor network consists of spatially distributed, autonomous devices, locally measuring some physical quantity (e.g., pressure, temperature, sound), while appropriate processing of the acquired signals allows performing the desired task (e.g., fire detection, pollution monitoring, landslide detection) [30]. The sensors share the wireless medium, used for communication between the nodes. The design of the system is constrained by multiple factors: low energy/complexity requirements (energy supply determines the node lifespan); unreliable communication (wireless medium); possible node failure (deployment in harsh environmental conditions). Motivated by the ubiquitous applications, the research on sensor networks envisages different aspects: on one hand, physical layer and hardware problems are studied; on the other hand, distributed algorithms are developed to acquire and process the data exploiting the network structure. Many issues can be considered, such as: the minimization of the energy necessary for data collection, storage, processing and communication; the approach to different network topologies, to environmental obstacles and to perturbations due to quantization, noises, or failures; the optimization of the network in terms of sensor density; the study of the optimal strategies to recover the desired information.

State-of-the-art applications involving ad-hoc wireless sensor networks are now based on mature technology (e.g., explicit routing of data, ZigBee communication standards, centralized signal processing and optimization techniques) [31], [32]. Usually, the measurements are locally acquired by the sensors and then conveyed to a central unit, in charge of their processing and transmission outside the network, via a gateway. The deployed technological ensemble, however, does not fully exploit the potential provided by the distributed nature of the system setting. Alternative solutions accounting for the distributed nature of sensor networks have been explored in the literature in recent years, which are promising with respect to efficient use of the energy both for communication and processing of information.

In the energy budget of the system the cost of communication is an important burden. The wireless medium allows transmitted data to be received at multiple nodes with a fixed communication cost. Standard routing in wireless networks [32], however, models multi-user communication as a multiplicity of simultaneous point-to-point connections, thus inducing data duplication, and inefficient energy use. An alternative communication approach is given by network coding [33], [34], which exploits the broadcast of information to neighbouring nodes to achieve cooperative information dissemination. Network coding has been proven capacity-achieving in the case of unicast and multicast over packet wireless networks [35]; furthermore, it is decentralized (i.e. does not require coordination among nodes), and it is independent on the network topology [36]. All these features make network coding a promising candidate to achieve energy-efficient communication in multi-hop networks. Energy comparison of the alternative communication approaches (standard routing vs network coding) is, however, still missing in the literature.

Another opportunity to restrain the communication cost is given by the nature of the data exchanged in the network: since the nodes measure a physical quantity, the measures exhibit spatial and temporal correlation, which can be exploited to achieve compression. This can be attained prior to information transmission, leveraging on distributed source coding techniques [37], [38]. In case of network coded data delivery, an emerging alternative approach consists in exploiting the statistical structure of the data to allow successful network-coded data reconstruction even for rank-deficient network matrices. This allows to obtain joint network coding and compression [39][40][41]. Approximate data reconstruction using belief propagation on factor graphs [39] and [42] have been proposed as a means to comply with the low-complexity and low-consumption requirements on the devices. Although theoretical characterization of the error probability is available [39] for specific source and network models, the problems of algorithm convergence and transmission matrix design for general sources and network topologies remain still open.

In many scenarios, the network acquires the data and then conveys them to a fusion center which performs the processing and produces the output; in other applications all the computations are performed in-network, exploiting consensus techniques, and thus avoiding the need of data gathering [43][44]. This strategy can be advantageous in terms of communication energy requirements and robustness. The capabilities of each node in terms of storage, computation and communication are limited, but leveraging on the network structure significant computations can be efficiently performed if compared with a single powerful processor. Moreover, the deployment of sensors allows performing various tasks, e.g., monitoring and localization tasks over large environments, which could not be tackled by a unique data collector.

An interesting emerging distributed estimation strategy is the one based on a calibrated weighting and mixing of two previously employed estimation procedures: consensus and innovation. If certain network regularity properties are satisfied, consensus may be reached by means of both asynchronous and synchronous communications among nodes through gossiping [45]. An interesting convergence rate study for an averaging procedure is also presented in the same reference [45], deriving an upper and lower bound with disrespect to the initial network measurements set up. More recently, the idea of combining consensus with a local information augmenting innovation has been proposed in [46], [47], [48], [49]. Performance has been investigated addressing both consistency and convergence rate of the proposed distributed non Bayesian estimation algorithms. The described approaches have not been well investigated in a Bayesian estimation context and in a time variant spatial field estimation scenario. Spatial-temporal correlation in measurements is also an unexploited feature of the physical quantities undergoing estimation. Room for improvements in convergence rates is also a possibility. Belief propagation in the consensus procedure may be enhanced by exploiting some very recent results concerning decoding of LDPC codes [50].

Another important point is represented by data acquisition. Depending on the nature of the signal, of the task to be performed in the network, and on the type of signal processing (in-network versus centralized) the sensing operation can be optimized, to allow maximum efficiency. In [43], [44] the optimum trade-off between sensing cost and reconstruction quality is studied for the case of field estimation at the fusion center. Recently, compressive sensing has been proposed as an energy-effective technique, in the context of temporal and spatial field reconstruction [51].

2.1.3 Protocol channel decoding

Joint source-channel decoding (JSCD) consists of using at the receiver side the residual redundancy left in the compressed bitstream by the source coder at the transmitter side, in conjunction with bit reliability information provided at the output of a wireless channel or of a channel decoder, see [68] and the references therein.

The idea of JSCD has been suggested by Shannon in his 1948 paper [95]. However, first results on JSCD of theoretical sources appear more than 40 years later. Early work on JSCD, see, e.g., [60], [90], or [94], addressed the robust reception of quantized source indices, making explicit use of their correlation. JSCD of entropy codes was first addressed for tree-based codes, such as Huffman codes [92], and later extended to arithmetic codes [70], [91]. When the communication chain includes error-correcting codes (ECCs), as would be the case when some links are wireless, optimal decoding requires the joint exploitation of source redundancy and ECC redundancy [69], [71]. Such decoding can be implemented using an iterative approach reminiscent of turbo-decoding [63], [71]. JSCD of bitstreams generated by more realistic coders such as H.263, H.264, or JPEG 2000 have been proposed by [64], [65], [77], [85], and [97].

These JSCD techniques improve the link budget of a multimedia transmission system when compared to classical schemes. They are however not compliant with the standard protocol stacks in several ways: (i) they require exchange of soft information (e.g., likelihood ratios) between the channel decoder at PHY layer and the robust source decoder at APL layer; (ii) they are not compatible with the use of acknowledgment procedures: a packet received in error need not be retransmitted unless the robust receiver at APL layer cannot recover the error; (iii) the headers of packets at a given layer must absolutely be available without error since they contain information necessary for driving the layer in question (at the receiver); (iv) at some layers, packets may be aggregated in larger bursts to reduce signalization overhead [74], [75]. Transmission errors, unavoidable in a JSCD context, make the packet recovery, or packet synchronization (PS), quite difficult.

Problem (i) above can be circumvented in some conditions: a mobile receiver contains all the layers and can choose to forward soft values between layers. This may be performed using, e.g., the techniques developed in [76], [89], or [98]. Problem (ii) does not appear in situations where acknowledgement is not possible (broadcasting) and has been partly addressed in [66], with the help of Bayesian hypotheses testing, for other situations. In these contexts, an enhanced reliability may also be achieved via packet-level forward-error-correction codes (e.g., erasure codes) implemented at the upper layers of the protocol stack. The main compatibility problems seem to be the third and fourth ones: standard protocol stacks do not allow damaged packets to reach the APL layer, the main reason being that the errors may impact some essential information contained in the headers, which is necessary even for the robust APL decoders.

Joint Protocol-Channel Decoding (JPCD) aims at addressing these problems. JPCD exploits the redundancy present in the protocol stack to facilitate packet synchronization and header recovery. This redundancy is due to the presence of CRCs and checksums at various layers of the protocol stack, as well as from the structure of these headers. In fact, within a protocol layer, the contents of headers present a high temporal correlation, while at a given time instant headers from various layers of the protocol stack can also be correlated. These correlations have been identified and exploited to design Robust Header Compression (ROHC) mechanism [61], but it is not clear that ROHC will be indeed used in the wireless context, due to the impact of an error at this level. This approach is useful in the context of mixed wired and wireless data transmission, and was first used to improve the efficiency of various layers of the protocol stack, see, e.g., [79], [86], [80], [83]. For example, compared to classical approaches, a priori knowledge of some parts of the packet headers may help synchronization [88] and channel decoding [73], more reliable header recovery may be performed [81], [83], [86], or aggregated packets may be more efficiently delineated [57], [59], [67], [79], [80], and [87].

2.1.4 Energy efficient probing in CSMA based multi-rate ad hoc networks

The energy efficiency of the CSMA protocol is analyzed in the context of several different standards. To evaluate the energy consumption of the IEEE 802.11 protocol, Bononi et al. [103] and Bruno et al. [104] analyzed the slotted p-persistent CSMA to evaluate the tradeoff between the throughput and the energy efficiency. In addition to these analyses of the p-persistent CSMA, Chan et al. [105] compared the energy efficiency of the slotted non-persistent CSMA against p-persistent CSMA since most of the MAC protocols for power-constrained devices employ non-persistent CSMA to eliminate idle listening. There are also other studies which analyze the energy consumption of CSMA based standards. For the IEEE 802.15.4 standard, energy consumption of the slotted non-persistent CSMA is analyzed in [106][107]. Similarly, energy consumption of slotted CSMA/CA is analyzed for uplink traffic in IEEE 802.15.4 networks [108]. Most of the abovementioned studies are confined to a specific standard and do not consider cross-layer energy efficiency. Thus a fundamental open issue is to develop energy efficiency models that can be applicable for CSMA-based standards in general. In the next section the main open issues in the area are summarized.

2.1.5 Summary of open issues

2.1.5.1 Open Issues on resource allocation and scheduling strategies for energy harvesting devices

Based on the above discussion, the following open issues in this area can be identified.

1. More elaborated statistical models for the energy packet arrivals have to be developed. These models could depend on the particular hour of the day and/or different environmental aspects.
2. Precise models of the energy consumption of the different components in the radio frequency chain and the decoding stage should be developed. It is important to

emphasize the relation between the energy consumption and the communications data rate.

3. Power minimization and resource allocation techniques for a multiuser scenario where the transmitter is an energy-powered device. The current literature deals with a simplified scenario (considering only two receivers) that needs to be generalized.
4. Power minimization and resource allocation techniques for a multiuser scenario where the terminals are energy-powered devices.
5. Power minimization techniques should be addressed in a relay network where the relays present in the network are nodes with battery limitations. Path optimization based on energy consumption considering the relation with data rate.
6. User scheduling for the case of multiuser MIMO scenario when the users are battery powered devices. Main goal could trade-off sum-rate and lifetime of the network.
7. User scheduling for the scenario considering wireless energy transfer scenario where two types of users need to be scheduled: harvesting users and information users.

2.1.5.2 Open issues on energy-efficient data collection and estimation in wireless sensor networks

Wireless sensor networks are a very wide field of research, involving many research communities. With respect to energy-efficient communications in WSN several open research issues are identified, a summary of which is listed herein.

1. The QoS metrics considered in the literature for the evaluation of the performance of a WSN do not include energy consumption. A theoretical framework for energy profiling needs to be devised.
2. The energetic profiling of the system depends mainly on three factors: signal acquisition, signal processing, and communication cost. In standard design solutions these functions are independently performed. If a distributed approach is taken (e.g. distributed processing, data dissemination in the network), however, there is inter-relation between them. Theoretical tools for trade-off identification need to be developed.
3. Communication in WSN can be achieved either using explicit routing of information, or via data dissemination techniques (e.g. network-coding based data dissemination). These two concurrent approaches have not been compared in terms of energy efficiency.
4. The physical nature of the measurements collected in the WSN entails strong temporal and/or spatial correlation structure in the signals. This can play a crucial role in the efficiency of both communication (e.g. allowing distributed compression), and distributed signal processing (e.g. decreasing the time of convergence of iterative algorithms).
5. Distributed estimation techniques via consensus are a very promising tool for distributed signal processing in WSN. Enhancement of the performance of these algorithms may be achieved in the Bayesian framework, by coupling with techniques based on graphical models (e.g. belief propagation algorithms).
6. When the task of the WSN is the reconstruction of a common quantity measured by all agents, compressive sensing might be employed to perform energy-efficient signal acquisition. When reconstruction is performed in a distributed fashion, however, theoretical analysis of the convergence rate and of cost-accuracy trade-off is missing.
7. When distributed communication and signal processing are implemented in the WSN, node failure, link failure and topology change can easily compromise the functioning of the system. It is thus necessary to develop tools able to assess the robustness of the communication and signal processing algorithms against these events.

2.1.5.3 Open issues on protocol channel decoding

Several open issues have still to be addressed with respect to the use of JPCD techniques.

1. JPCD decoding techniques have to be studied when applied to robust header compression (ROHC). ROHC reduces the redundancy in headers, but compressed headers become more sensitive to transmission errors. ROHC used in broadcast, due to the absence of retransmission, leaves some redundancy in headers. ROHC may thus benefit from JPCD.
2. In protocol-assisted channel decoding, a priori probabilities of pilot bits are assumed to be known. This hypothesis is difficult to satisfy in realistic contexts, where these a priori probabilities have to be estimated, e.g., from already correctly received packets. The impact of estimated “a priori” probabilities on the performance of protocol-assisted channel decoders has to be evaluated to design the best estimators.
3. Most of the results in JPCD were for unencrypted headers, or for packets encrypted with simple (memoryless) encryption systems. The impact on JPCD techniques of more sophisticated encryption systems has to be evaluated.
4. JPCD techniques have considered simulation scenarios with a restricted number of users, for example connected to the same Wifi access point, assuming that medium reservation has already been performed successfully. JPCD has clearly a role to play in this medium reservation phase, for example to improve the decoding of RTS/CTS packets in WiFi.
5. Reliable synchronization and channel estimation using JPCD techniques have been considered in relatively simple scenario, such as 802.11a. Extension to more sophisticated protocols has to be considered.
6. Intermediate protocol layers of multimedia transmission systems tend to incorporate rate-less codes. The compatibility and the potential benefits of JPCD techniques in this context have to be evaluated.
7. JPCD allows driving potentially corrupted packets to the upper layers of the protocol stack. Nevertheless, when packets are too corrupted, it is usually better to ask for a retransmission, since it will certainly not be recovered by JSCD techniques at the application layer. Tools to evaluate the reliability level of potentially corrupted packet should thus be developed.
8. More generally, the compatibility of retransmission mechanisms such as ARQ or HARQ with joint decoding techniques has to be evaluated. Joint decoding techniques, may for example modify the way the redundancy is incremented in HARQ.
9. A real-life evaluation of the benefits of joint decoding techniques has to be performed. This requires the development of receivers implementing several joint decoding techniques and receiving data through a real channel or a realistic channel model. The choice of modulations and coding schemes may then be affected, in downlink, the usual application context considered by joint decoding techniques, but also in uplink, where an energy consumption optimization may be considered.

2.1.5.4 Open Issues on energy efficient probing in CSMA based multi-rate ad hoc networks

A summary of the open issues is presented below.

1. In a broader sense, one of the main open problems is reducing the energy consumption of wireless devices to improve battery lifetime, to reduce energy costs and to minimize the environmental effects.
2. Most of the previous energy efficiency studies either focus on the MAC layer or the physical layer in isolation. Cross-layer energy efficiency of random access protocols has not been sufficiently evaluated. To achieve more efficient communications, both layers should be considered jointly.
3. Most energy-efficiency studies in the literature focuses on a specific standard. However, to obtain energy efficiency principles which can be applicable for a wide range of protocols, a more general analysis is required.
4. There is a growing interest on designing CSMA algorithms with optimum throughput performance. On the other hand, energy efficiency of these algorithms has not been

considered jointly with their throughput performance. Since throughput optimization may come at the expense of energy efficiency, these methods have to be evaluated in terms of energy consumption.

5. Implications of the physical layer adaptation methods on the MAC throughput performance have not been studied previously. However, physical layer techniques have a significant effect on MAC performance by changing frame lengths and loss probabilities.
6. Implementation of energy efficient techniques in a distributed manner is also an open challenging problem.

2.2 Techniques for interference handling and mitigation

The problem of efficient coexistence of various wireless systems operating in the same or neighbouring frequency bands, in the same time and at given location has became more apparent during the last couple of years. By looking the existing frequency allocation plans one can observe that most of the frequency resources have been assigned to specific services that use specific radio access technologies. Thus, it is not straightforward to promote new services with new radio access technologies in adjacent bands, since it requires efficient management of the unwanted signal emission outside the nominal band. This interference phenomenon is also very important in the context of existing wireless systems, where the problem of unwanted emission appears to be significant in dense HetNet deployments with a large number of users. Thus, the application of effective interference mitigation and management techniques become a necessity for a variety of scenarios. In this section the analysis will be concentrated in interference handling and mitigation techniques (i.e., how to control and reduce interference) in the identified research areas of the second task: (i) advanced MIMO techniques and (ii) filtering and adaptive signal processing techniques. In the following section (section 2.3) the focus will be on the interference management – for a given interference level – in HetNets scenarios.

2.2.1 Advanced MIMO techniques for low-interference transmission

Recently, Multiple Input Multiple Output technique has gained the attention of many research centers and universities. The application of MIMO solutions provides the opportunity not only for throughout improvement but also for guaranteeing effective coexistence between one or more users located in the close vicinity. Although hundreds of scientific papers have been devoted for interference mitigation In the MIMO or MIMO-OFDM case, the problem of MIMO-FMBC is not explored. This is particularly important since FBMC systems seem to be one of the solid candidates for being the successor of OFDM modulation, mainly due to its great spectral features. Moreover, the issue of interference handling in the context of so-called virtual MIMO scheme, e.g. for wireless body area networks, needs further investigations.

2.2.1.1 Interference problems in FBMC/GMC systems

The possibility of equalizing the entire band with a reduced complexity has been one the main reasons to move from single carrier to multicarrier techniques. In addition, multicarrier systems allow serving several users in the same time slots, which allows flexible resource sharing. In this sense, the Orthogonal Frequency Division Multiplexing (OFDM) is the most prominent multicarrier modulation. The main advantage of the OFDM technique stems from the fact that the global communication system can be modelled like a set of parallel flat fading channels. In addition, the modulator and the demodulator can be implemented with a reasonable complexity. Nevertheless this comes at the price of transmitting redundancy in the form of a Cyclic Prefix (CP) and shaping the subcarrier signals with the rectangular window, which has poor stop-band attenuation. In this regard, the Filter Bank Multicarrier Modulation (FBMC) is a potential substitute that is designed to achieve maximum bandwidth efficiency. It shapes the subcarrier signals with frequency localized waveforms, which may have a faster decay than the sync-like shape. As a result, FBMC has an increased robustness against synchronization errors and narrowband interferences with respect to OFDM [109].

FBMC has its origins in the sixties, when Chang devised a multichannel transmission system in which amplitude modulated (AM) data is transmitted in parallel by band-limited pulses [110]. Soon after, Saltzberg in [111] extended the scheme envisaged in [110] and proposed a parallel quadrature-amplitude modulation (QAM) transmission. The modification consisted in staggering in-phase and quadrature components of symbols drawn from a QAM constellation. Until recently, these schemes have received little attention because of the hardware requirements. However, this has been solved to some extent thanks to the possibility of efficiently implementing the synthesis filter bank and the analysis filter bank [112], [113]. Because of this, FBMC is gaining momentum. It is worth mentioning that the emphasis of this work will be on the Saltzberg's scheme where FBMC is based on the OQAM transmission, which is known as (FBMC/OQAM) or (OFDM/OQAM) [114]. On the negative side, FBMC/OQAM has an increased complexity when compared to OFDM and is affected by intrinsic interference since the orthogonality conditions are satisfied in the real field. As a consequence, before the real part is extracted the channel has to be perfectly equalized. In this sense, we can find several publications in the literature that address the equalizer design, [115]-[118]. Based on the results in [115]-[118], we can conclude that in the presence of highly frequency selective channels, the orthogonality is only restored if the equalizers perform a multi-tap filtering. To mitigate the noise enhancement effect yielded by the equalizers, some authors have focused on the design of linear precoders [119]-[120]. However, this topic is not fully explored.

2.2.1.2 Interference handling in Body-Area-Networks – Virtual MIMO concept

Body Area Networks (BANs) are at the core of the next generation of wireless systems [121]. A practical arrangement often used for characterizing communications in BANs, regarding the transmission channel, is to have on- and off-body communications. On-body communications deal within on-body networks and wearable systems. Most of the channel will be on the surface of the body, with both transmitter (TX) and receiver (RX) antennas located very near the body. Communications from a wearable or on-body device to an external base station are termed off-body. Only one antenna of the communication link is on the body, and most of the channel is off the body and in the surrounding space. In such a channel, the body almost does not interfere with the propagation environment, but its presence leads to changes in the antenna performance, hence, having a strong influence in the overall behavior of the radio channel.

BANs have a wide range of potential applications, the major interests being health care and patient monitoring, sports monitoring, security/military/space applications, business and multimedia entertainment, among others. An increased research on the different layers of BANs has risen recently, as these networks are quite different from traditional wireless ones. Some of their general requirements are interoperability, reliability (at system and cross-system levels), low complexity, security, privacy, and energy efficiency. The particular characteristics of BANs, like the influence of the user's body on the radio channel, the dynamics of the user, the short distances of propagation, the link geometry variability, as well as the arbitrary orientation of antennas, demand for explicit solutions that enable the reliability of BAN communications, especially for applications demanding low bit error rates (e.g., healthcare and battlefield).

Cooperative techniques are a natural option to save power, increase the connection reliability, and overcome the effects of deep fading in BANs [122], [123]. Virtual MIMO is one of the strategies, using clusters of nodes, on the TX or/and RX sides, then combining multiple independent paths to behave like multi-antennas systems. The use of MIMO in BANs has been studied essentially through measurements, held in anechoic chamber, office, or lab environments; (see [124]-[126]).

Some preliminary studies based on simulations have analyzed the correlation between channels and their power distribution, as means to obtain the optimum placement of antennas on the body in MIMO systems. It was previously found [127] that, for off-body systems, the antennas located on different sides of the body (e.g., one antenna is located on the back and the other on the front) are the less correlated ones. It was also found in [128], a joint analysis of the correlations between on-body channels and their power distribution, that the locations on the ears and on the arms are the best options for a virtual on-body MIMO system.

2.2.2 Advanced filtering and adaptive signal processing (OOB, PAPR, SIC)

Sometimes the transmission front end of licensed terminals introduces distortions to the neighbouring systems. To compensate that, one approach is to reduce the level of out-of-band radiation by appropriate signal processing or by application some advanced algorithms for interference suppression. As these problems have been tackled for many years in the context of OFDM, these aspects are not solved for other modulation schemes, such as the already mentioned FBMC.

2.2.2.1 Peak-to-Average Power Ratio problem in multicarrier signalling

The transmitter consists of different non linear components like digital to analog converter, mixer and power amplifier. The main concern is the high power amplifier (HPA). High power amplification is required to transmit an RF signal and to counter the channel fading affects. When a signal with high power fluctuations is passed through HPA it can be distorted. To avoid that, we target at HPA operation in its linear region so that the peaks of the signal to be amplified never enter into non linear amplifier zone. This way of HPA operation leads to a high battery consumption penalty. Therefore, another approach is the processing of the signal to be amplified before the power amplification in order to reduce the peak values of the power fluctuations of the signal. This would allow the HPA operation in a high efficiency zone, reducing the battery consumption. These power fluctuations are described by various terms in literature, the most common of all is the PAPR. It is defined as the ratio between maximum instantaneous power and mean instantaneous power. Normally the PAPR value determines the signal fluctuations and, since it varies from signal to signal, it is a random variable. Thus, it is always recommended to perform statistical analysis of PAPR and consequently representing it in terms of its distribution function.

There are various PAPR reduction techniques presented in the literature. These methods include Clipping [129], Clipping and Filtering [130], [131], Deep clipping [140], Selective Mapping (SLM) [132], Interleaving [133], Tone Injection [134], Active Constellation Extension (ACE) [135], Partial Transmit Sequence (PTS) [136], Coding [137], and Tone Reservation (TR) [134] etc. There are also papers dealing with the classification of those methods [138], [139]. The main objective in all these methods is to balance all key parameters in the OFDM system (BER, spectral re-growth, complexity, additional power, date rate loss, etc.).

Today, the most promising techniques are Tone Reservation and ACE. They have been adopted in DVB-T2 standard as options. In this deliverable, we will only focus on Tone Reservation (TR). TR is an efficient method to reduce PAPR; it is based on adding an information data-block-dependent time domain signal to the original multi carrier signal to reduce its peaks. The objective is to find a time domain signal c which, when added to time domain multi carrier information signal x, decreases the peaks in the information signal in such a way that PAPR(x+c) < PAPR (x). This goal is achieved with the help of vector C (C=fft(c)) with the same size as data block X ((X=fft(x)). The vectors X and C are orthogonal to each other, i.e., X has zeros where C is non-zero and has values on zero valued C indexes. These non-zero values are called Peak Reducing Carriers (PRCs) or corrected carriers and the method is occasionally referred to as PRC because of this fact.

In DVB-T2, 1% of carriers are dedicated to PRC which implies a very small date rate loss and a PAPR reduction capacity around 3-5 dB, depending on the algorithm used to optimize the PRC. In addition to PAPR reduction, linearization should also be taken into account in order to improve the overall budget of the transmitter. It is considered that PAPR reduction and linearization have to be performed jointly, and not separately as it is so far [141], in order to enhance both efficiency and linearity.

2.2.2.2 Out-of-Band emission problem in multicarrier signalling

An important problem in the future wireless systems is the appropriate transmitted signal spectrum shaping. It is essential for neighboring (in frequency) systems to occupy only frequency bands assigned to them, while minimizing the Out-of-Band (OOB) radiation that interfere to other wireless systems. It is most apparent in the case of Non-Contiguous Multicarrier Systems (NC-OFDM), where a narrowband system (e.g. wireless microphone) is surrounded, on both sides of its spectrum, by multicarrier system as shown in Figure 2-1.

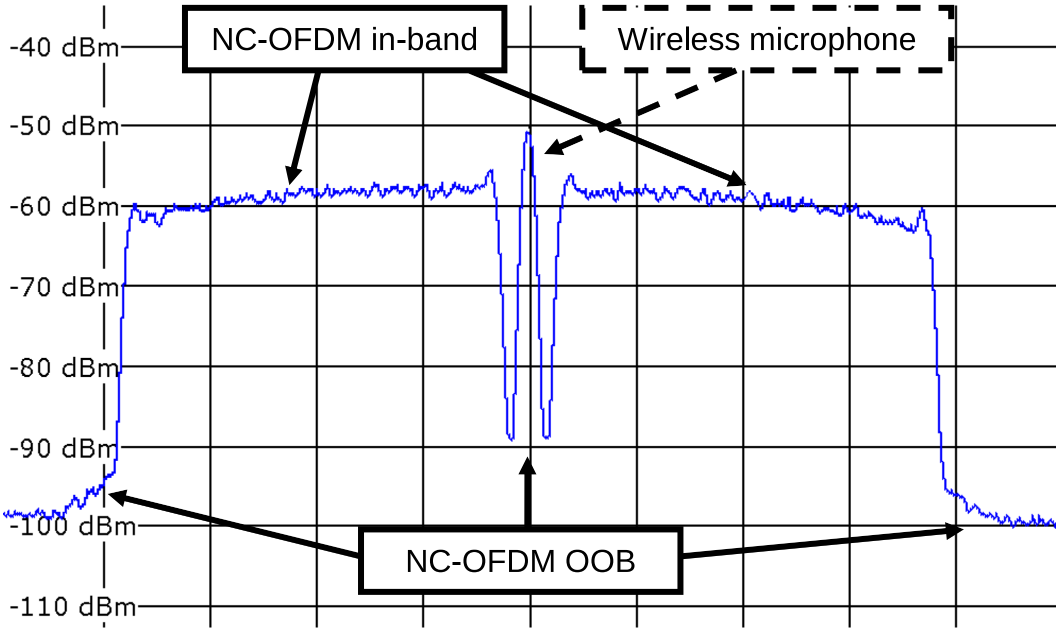

Figure 2-1: Power spectrum density of two signals: NC-OFDM and wireless microphone transmission vs frequency domain

The OOB radiation in NC-OFDM systems is caused by two reasons: intermodulations of transmitted signal on nonlinear elements of RF front-end, and subcarrier spectrum sidelobes being the result of OFDM symbol shape. The first source of OOB interference is connected to the PAPR metric described in the previous section. While decreased signal PAPR allows the use of HPA amplifier in a more efficient way, clipping of signal peaks in time domain causes rise of intermodulations. The solution for this problem is PAPR reduction methods and HPA predistortion techniques described in the previous section. The subcarrier spectrum sidelobes are caused by time-domain shape of OFDM symbol [142]. Each subcarrier, in time domain, can be presented as continuous wave with a given initial phase and amplitude, i.e. transmitted data symbol. As the length of OFDM symbol has to be limited to only $N+N_{CP}$ samples (where N – IFFT size and N_{CP} is cyclic prefix length), it can be presented as cutting $N+N_{CP}$ samples of infinitive continuous wave with rectangular window. In frequency domain in can be showed to be convolution of comb of dirac deltas (continuous waves on each subcarrier) with sync-like spectrum of rectangular window.

The most straight-forward solution would be to design a digital filter to reduce OOB spectrum sidelobes. However, such a filter would have large number of taps in order to provide flat in-band characteristic and strong OOB radiation suppression, especially in case of narrow and deep notches. Algorithms utilizing properties of NC-OFDM signal can suppress spectrum sidelobes more efficiently with lower computational complexity requirements. There is a number of methods for reduction of subcarrier spectrum sidelobes in the literature, e.g. time-domain windowing [142], insertion of cancellation carriers [143], [144], addition of adaptive symbol transition [145], subcarrier weighting [146], multiple choice sequences [147] or some precoding schemes [148]-[150]. Quite exhaustive description and comparison of these and other subcarrier spectrum sidelobes reduction methods can be found in [144].

Although many algorithms have been already designed, there is still room for new algorithms providing low OOB radiation level without increasing PAPR metric and being acceptable from computational complexity point of view. The biggest issue is how to efficiently combine both subcarrier spectrum sidelobes and intermodulation reduction in one spectrum shaping algorithm. It was already observed that reduction of spectrum sidelobes (e.g., using the cancellation of carriers method [144]) increases PAPR.

2.2.3 Summary of open issues

2.2.3.1 Open issues on advanced MIMO techniques for low-interference transmission

Based on the above discussion several open issues for further investigation and development are identified:

1. Various precoding schemes have been developed for 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.
2. One critical topic is the study of the impact of precoding on the average transmitted power. The goal is to verify how various precoding techniques influences the transmit signal in terms of energy efficiency and transmit power characteristics. Uncontrolled transmit power variations caused by the precoding algorithms could potentially lead to interference increase.
3. The problem of high variation of the OFDM signal envelope is well-known for many years. A great number of algorithms have been proposed to address it. Although some work has been performed in order to investigate the peak to average power ratio (PAPR) characteristics in the context of FMBC systems, more research work is needed in order to define efficient PAPR reduction procedures and estimate the approximation functions of the PAPR coefficient. Lower PARP will lead to better power amplifier efficiency and lower out-of-band emission.
4. An open issue for further investigation is the proper design of power allocation strategies to reduce the PAPR and the out-of-band radiation in FBMC systems as it can be for OFDM.
5. The problem of efficient channel modeling in the context Wireless BAN 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 the virtual MIMO systems, 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.
6. 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.
7. The FBMC modulation scheme is affected by intrinsic interference and the transmitted symbols are non-circular. These specificities highlight the necessity of

analysing the transceiver chain to characterize some metrics such as the average transmitted power.

8. 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 has not been determined.

2.2.3.2 Open issues on advanced filtering and adaptive signal processing

Some identified open issues are the following:

1. 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 need to be addressed.
2. PAPR analysis and algorithms have been usually designed for OFDM systems. Further work needed to adapt those solutions for non-contiguous multicarrier systems.
3. 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.

2.3 Techniques for resource allocation and interference management

Resource allocation (RA) is an active field of research for many years, following the development of new wireless systems and networks. As the radio access technologies evolve, along with new protocols and new network topologies, the role of resource allocation techniques becomes more complex and important for the efficient use of the available resources.

As stated in the introduction, a prominent approach to address the increase in data rate demands and the respecting spectrum crunch is the addition of more hardware nodes that allow the communication between them in lower power levels and thus allow more often the reuse of the available spectrum. A manifestation of that approach is the HetNet concept where a network is consisted of a variety of base stations with different characteristics (power, coverage, antenna patterns, etc.). The complexity of those types of networks poses the greatest challenges from the RA and Interference Management (IM) point of view and thus it will be the main focus of the SoA analysis presented herein. In the following subsections the concept of HetNets and the respecting generic challenges are presented. The main current trends and developments in RA and IM techniques are more thoroughly discussed and the fundamental issues open for further investigation are identified. Since the available literature in this area is significantly large, the analysis herein will be concentrated on three thematic areas which are closely related to the partners' research activities in the WP: (i) developments and challenges in the interference coordination techniques in LTE, (ii) opportunities and challenges in shared use of spectrum (e.g. TVWS) in the HetNet environment, and (iii) analysis and open issues directly related to game theoretic approaches to RA and IM.

In parallel with the HetNet concept the research community has also been focused in Machine-to-Machine communications (M2M) which are defined as a form of data communications which do not need human interaction. Currently, the most interesting applications from the commercial point of view are related to smart grids, automatic water and gas meter readings, and other related types of services. However, the M2M application space is vast and includes security, health monitoring, remote management and control, intelligent transport systems, ambient assisted living, etc. Furthermore, M2M is more than just connected devices sharing data; it is also about collecting and distributing the data efficiently, often in real time and with desired QoS requirements, in terms of e.g. latency. The communication network plays an important part of the ecosystem and its ability to support

M2M services and traffic requirements will be crucial for such a distributed setup. Based on that view point it is envisioned that M2M communication will be eventually integrated into the HetNet concept. Herein, in the last subsection, an overview of Machine-to-Machine (M2M) networks is provided along with the related SoA analysis and the relevant open issues.

2.3.1 Heterogeneous Networks concept and challenges

Cellular networks have traditionally followed homogeneous deployments of macro cells, with some micro or pico cells deployed under special situations (e.g. traffic hotspots, etc.). The base stations work under similar characteristics, such as transmit powers, antenna patterns, number of serving users and backhaul connections. In these scenarios, the coverage and the interference minimization can be carried out by means of sophisticated network planning techniques [165]. However, with the exponential growth of the data demand, cell splitting, additional bandwidth and new cellular deployments are necessary to fulfil the needs in coverage, capacity and high data rates. Moreover, it is very common that the data traffic is presented in hotspots; that is for example in stadiums hosting big events or campuses, and that the traffic requirements suffer very significant fluctuations in different areas and periods of time. In this context, the traditional deployment of macro cell sites, apart from being costly, is not efficient to adapt to the uneven user distributions and traffic demand [159]. In addition, cell splitting is complex and the usage of more frequencies is usually very difficult due to the scarce nature of the radio spectrum [165].

Standardization bodies have turned to alternative cost-effective solutions that will allow the further improvement of the network performance by deploying more advanced network topologies, known as Heterogeneous Networks (HetNets) (Figure 2-2). Based on [159], [160], [161], [162], a HetNet can be defined as a network comprised of traditional large macrocells and smaller cells including microcells, picocells and femtocells. HetNets can also involve the combination of different radio access technologies, such as WiFi and WiMax, for traffic offload. HetNets are envisioned to be *the* future in wireless communications since they allow flexible cost-effective deployments in order to provide additional coverage in areas that they cannot be covered by the macro-cells and enhance the capacity in hotspots [159].

For the formation of a HetNet, a variety of low power cells (Low Power Nodes: LPN) is used. These are classified according to their different characteristics, such as the size and the transmit power.

Pico cells follow the same concept as the e-NodeBs; however they utilize lower transmission powers and they cover smaller areas. Moreover, they cannot be equipped with sectorized antennas (only omni-directional). Their deployment is carried out in an operator planned manner in order to serve indoor or outdoor applications. Depending on the deployment, the transmit power may vary between 250mW and 2W for outdoor and up to 100 mW for indoor scenarios [160]. In LTE the connection to the core network is carried similarly as with the e-NodeBs, therefore pico cells can make use of the X2 interface and benefit from the Inter-Cell Interference Coordination (ICIC) techniques.

Femto cells on the other hand, are intended to serve only indoor scenarios. They employ only omni-directional antennas and their transmit power does not exceed the 100 mW. Due to the low transmit power the interference is kept at low levels. In addition, since femto cells offer small coverage, the distance between the user and the femto cell is quite low, providing in this way better signal quality [167]. The installation is carried out by the consumers in an unplanned manner, thus operators are not aware of the changes that may occur to the network structure and this becomes one of the greatest challenges. Moreover, femto cells are not connected to the backhaul of the cellular network; instead they utilize the DSL connection or the cable modem of the subscriber. With that approach however, in LTE, the X2 interface is not accessible, thus classic ICIC techniques cannot be implemented. In order to mitigate the femto related interference alternative techniques should be developed. Finally, femto cells can operate in two modes, namely Open Subscriber Group (OSG) and Closed

Subscriber Group (CSG). In the CSG mode only a specific group of users is allowed to access the network, which is defined by the subscriber who installed the femto cell. In the OSG mode, the femto cell can be accessed by all the users [165].

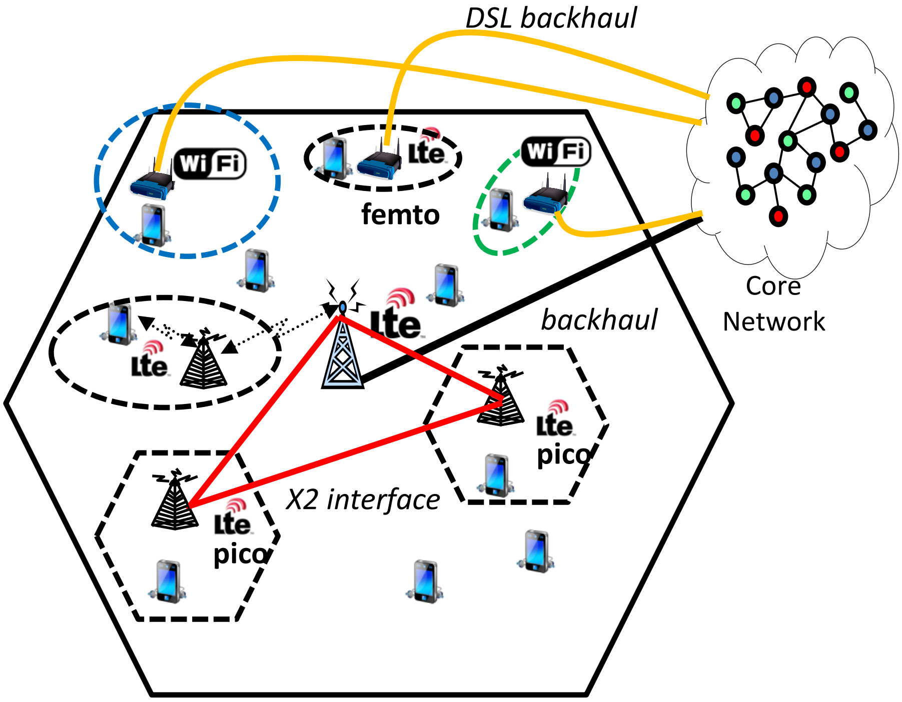

Figure 2-2: HetNet Topology example

According to [159], the addition of LPNs in a traditional cellular network enhances significantly the performance of the network, while offering improved coverage. Figure 2-3 presents the gain in the spectral density depending on the network topology. As it can be observed, the gain is tremendously increased as cells of smaller radius are used to serve the data traffic.

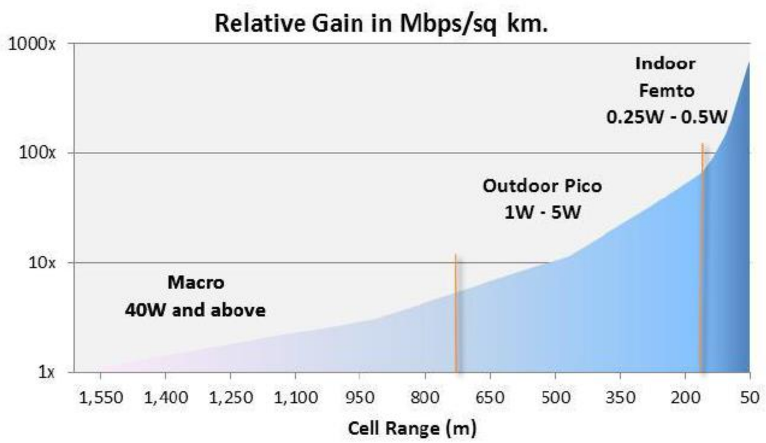

Figure 2-3: Spectral Density Gain with respect to the network topology [159]

Moreover, simulation results conducted by 3GPP [166] have shown that with the deployment of HetNets a macro cell can provide higher capacities since the number of users that it serves is decreased. As a result, less users share the same capacity thus allowing higher data rate transmissions. In addition, the users that are served by the small cells (pico/femto) experience high quality transmissions with higher data rates and due to the low power transmissions the battery life of the terminals is significantly extended.

Despite the attractive features of the HetNets, several challenges arise due to the co-existence of such diversity of technologies, as identified in [162]. These issues include the necessity for new metrics in order to accurately evaluate the performance of the HetNet network. The outage probability distribution and the area spectral efficiency are considered to be two prevalent metrics. Moreover, the way the network topology used to be modelled must be changed since the deployment of the small nodes usually takes place in areas under the coverage of a macro cell and does not follow a regular rule. In addition to this, due to the disparity among the transmit powers, the coverage area of each node differs substantially. However, the same does not apply for the uplink (users transmit with the same power), thus dissimilarities in the SINR of the DL and UL may occur. As such, the option that a user may be connected with different cells during the DL and the UL transmissions should also be taken into account. This will imply that the interference for a given user will require different models in the DL and in the UL. Furthermore, the way the users are associated to each cell needs to follow other criteria than those used in traditional macro cellular networks where usually the user is associated to the cell from which it receives the highest power. Similarly, for the user mobility alternative solutions should be considered. The handoff decisions should be based on different parameters, such as the speed of the user (if a user travels too fast it would be suboptimal to perform several handoffs between LPNs and macro cells) and the overall interference.

2.3.2 Interference Management approaches

Proper resource and interference management techniques are necessary to cope with the above identified issues and to increase network performance. A classification of the various approaches and techniques addressing the interference management problem is presented in [200]. The paper provides a coverage and interference analysis for selected OFDMA macro/femtocell scenarios. It defines as *cross-layer* (or *cross-tier* as in [201]) the situations in which the interferer and the victim belong to different network layers (e.g., femtocell and macrocell layer). *Co-layer* (or *co-tier* as in [201]) is defined as the situation when the interferer and the victim are in the same layer (e.g. femtocell-to-femtocell interference). Furthermore, a categorization of the different approaches of subchannel allocation management is proposed. An approach to eliminate cross-layer interference is to divide the spectrum into two parts (*orthogonal channel assignment*), one fraction for the macro-layer and one fraction for the femto-layer. This is optimal from the cross-layer interference point of view but is inefficient in terms of spectrum usage. *Co-channel assignment* is the other approach which is more efficient but also more challenging. The orthogonal assignment can be further categorized based on the type of spectrum allocation used: *static*, depending on the geographic area and *dynamic* based on the traffic and users' mobility. In the co-channel case two distinct categories are identified: *centralized* and *distributed*. In the centralized option there is a central entity that does the allocation for all layers, while in the distributed case each LPN manages its own subchannels. The later can be further divided to *cooperative* and *non-cooperative* approaches. The use of databases for the exchange of information between the different layers has also been considered. In [202] the concept of a Radio Environmental Map (REM) has been investigated as a tool to gather useful information for spectrum management and resource allocation purposes.

2.3.3 Inter-Cell Interference Coordination in LTE

In the LTE context three general types of *Enhanced Inter-Cell Interference Coordination* (eICIC) methods are considered, which are classified as Time-Domain, Frequency-Domain and Power Control [169]. 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. The different sub-sections will present in more detail these methods and the corresponding techniques in the literature.

Time Domain Inter-Cell Interference Coordination

In the Time-Domain method, the users that suffer from interference are assigned resources in specific time periods where the interference is suppressed [163]. Two types are considered, the *subframe alignment* and the *OFDM symbol shift*.

The subframe alignment is a technique introduced in Release 10 that employs the *Almost Blank Subframes* (ABS) (see Figure 2-4). During these subframes the *aggressor* cell (the cell that generates interference) periodically stops its transmissions, so that the *victim* cell can transmit under reduced interference conditions [159]. The word *almost* results from the fact that there is the necessity for some reference signals to be transmitted for backward compatibility purposes with the LTE Rel. 8 terminals. As such, optimization is also required in this scheme, in order to compensate the performances of the LPNs and the macro cells. In [170], a study has been presented on methods used for interference management in LTE networks composed by LPNs and macro cells. Two approaches are addressed, power setting and partial Time-Domain muting. It has been proved that depending on the scenario under study both approaches can reduce interference. A different approach is presented in [171], where the authors propose a distributed method that performs user classification among *victims* (users in CRE area) and *normal*. Then, they use dynamic programming to calculate the optimal number of ABS.

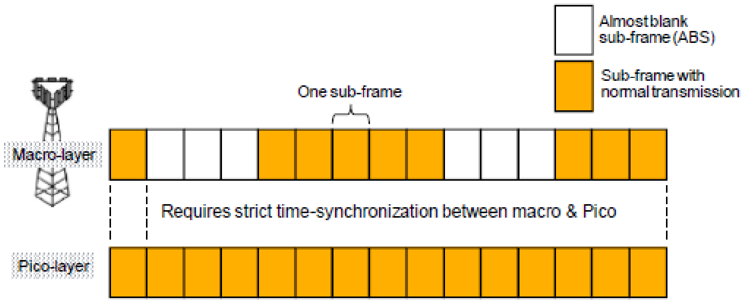

Figure 2-4: Almost Blank Subframes (ABS) [159]

On the other hand, OFDM Symbol Shift is a technique where the subframe boundary of the LPN is shifted by one or more OFDM symbols so that a difference is introduced with respect to the macro cell node. In this way, the control channels of the LPN and the macro cell do not overlap, thus interference is avoided. Nevertheless, interference on the data channels between the two nodes is still present [172]. To cope with this problem, two approaches are used; *PDSCH symbol muting* and *consecutive subframe blanking*. For an overview of these techniques the readers may refer to [172].

Frequency Domain Inter-Cell Interference Coordination

In the Frequency-Domain method, orthogonal transmissions of different users are achieved by assigning different frequency resources to the users in the different cells that can potentially interfere. The implementation of the orthogonality can be achieved both in a static and in a dynamic manner [163].

The assignment of different frequencies to different cells applying a frequency reuse factor has been in fact the traditional way how cellular networks have been deployed since its origins. With this classical approach the set of available frequencies was split in F groups, where F is the reuse factor, and each group was assigned to a different cell inside a cluster of F cells so that each cell only has 1/F of the total bandwidth. The lower the value of F the higher the efficiency that can be achieved, because each cell will have more bandwidth, but at the same time the higher the intercell interference that will be experienced, because there will be more cells using the same group of frequencies. With the appearance of LTE and the associated requirements for higher efficiencies, together with the higher flexibility provided by OFDMA technology, this frequency reuse concept was evolved towards the so-called Fractional Frequency Reuse (FFR) schemes.

In FFR the frequency reuse is not homogeneous throughout the whole cell coverage area. Instead, the cell area is divided in two regions, the inner and the outer region. Users in the inner part are located closer to the base station than users in the outer part and consequently, they are more protected against inter-cell interference. Furthermore, the available bandwidth is partitioned in two groups, the inner and the outer. The outer group consists of the set of sub-bands that can be assigned to the outer users, while the inner includes the frequencies that can be assigned to inner users. Several FFR techniques have been presented in the literature, which differ in the sub-band allocation and the transmit powers used in the inner and outer parts. In the following the Soft Frequency Reuse (SFR) and the Partial Frequency Reuse (PFR) will be briefly discussed.

SFR is a variation of FFR which targets to an efficient bandwidth utilization [173]. The main characteristic of the SFR scheme is that the whole bandwidth is available to all the sectors; however each sector can transmit in different frequencies with different powers for the inner/outer users, as shown in Figure 2-5. As it can be seen, the outer users are allowed to utilize only part of the spectrum with a reuse factor greater than 1 (equal to 3 in the example), while the inner users may also have access to the frequencies reserved for the outer users of another cell (see e.g. that cell 1 uses for the inner part f_0 and f_1 that are also used, respectively, by outer users of cell 3 and cell 1). This forces the restriction of the transmit powers of the inner parts to lower levels than the outer parts in order to reduce the interference of the network. Compared to other FFR schemes, with this technique it is possible to achieve higher data rates for the inner users, while the outer users do not suffer from high interference. With this approach, the spectrum efficiency can be significantly improved, although outer users still experience some interference from the inner part of other cells. Finally, it has to be referred that the transmit powers can be adjusted according to the desired reuse factor.

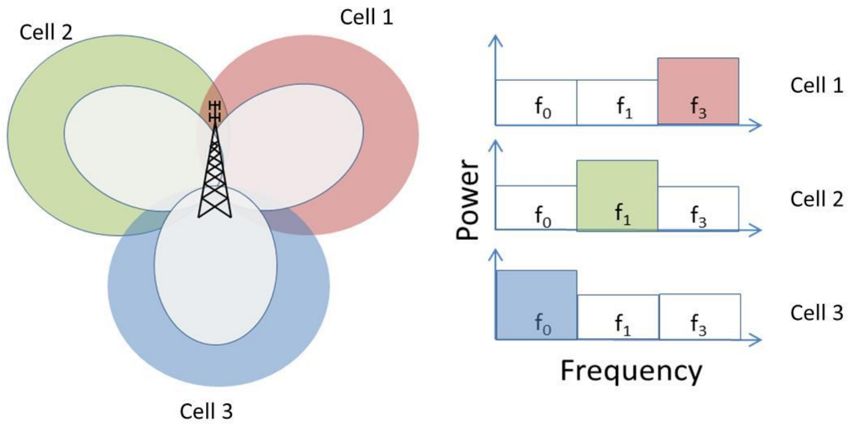

Figure 2-5: Soft Frequency Reuse

PFR reuse scheme (also called in some works strict FFR) follows a similar approach, but the available bandwidth is divided into the inner band which is assigned with a reuse-1 factor (Full Reuse) and which is common to all the cells, and the outer band which is assigned with a higher reuse factor (Partial Reuse) [175]. As such, the users located in the inner part utilize a common frequency, while the outer users benefit from the allocation of non-overlapping frequency sub-bands. The advantage of this strategy is the mitigation of the interference experienced by the outer users of the cell since neighboring cells utilize different frequency sub-bands, while keeping the interference experienced by the inner users in low levels. In Figure 2-6, an example of the PFR technique is presented, which allocates the inner band with reuse factor 1 and the outer with reuse factor 3. If we consider that the total bandwidth BW is divided in the inner part BW_1 and the outer BW_2, then the effective frequency reuse factor will be $BW/(BW_1+BW_2/3)$ [176]. As such, while PFR outperforms conventional frequency reuse schemes in terms of spectral efficiency; still the available bandwidth is not fully utilized [177].

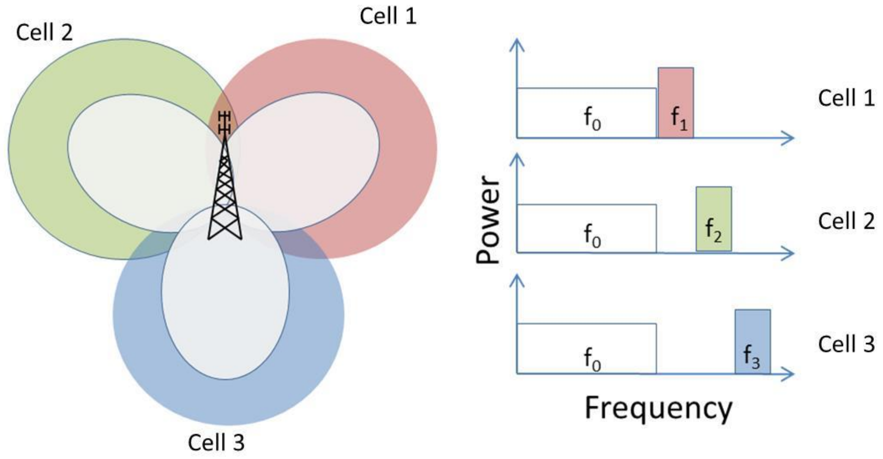

Figure 2-6: Partial Frequency Reuse

Despite the fact that the above presented schemes present sufficient improvements in terms of spectral efficiency and interference reduction, if the allocation of the resources remains static they wouldn't be able to adapt to the network changes, such as in spatial traffic loads that vary over time. The dynamic allocation results in even higher performances; as such research has been focused on the dynamic ICIC techniques. A Dynamic Fractional Frequency Reuse scheme has been presented in [178], where the resources are re-allocated depending on cell load variations. The proposed scheme makes use of a graph-based framework. Through simulations it has been shown that the proposed solution presents throughput and data rate improvement in scenarios with un-equal cell loads. In [179], a dynamic SFR scheme has been developed following a clustered base station coordination strategy. Simulation results have shown significant improvements in the edge users throughput compared to conventional solutions. Optimized schemes exploiting dynamicity were also studied for PFR scenarios. In [180], an adaptive PFR scheme has been developed based on an off-line genetic algorithm. Through simulations, it has been demonstrated that the proposed solution outperforms the classical PFR scheme in terms of edge user throughput.

However, every technology evolution is usually accompanied by a trade-off, where in this case results from the need for coordination between the nodes. As such, despite the significant improvements in the network performance offered by the introduction of dynamicity, extra overhead is presented from the necessity of information exchange (signaling). In LTE though, the coordination can be easily implemented thanks to the X2 interface. This interface allows the information exchange between the involved base stations (e-NodeBs) [181][182].

The above FFR schemes are usually applied to the macro cell tier, where most studies consider regular deployments. There are few works in the literature that have explored the applicability of FFR when considering multi-tier deployments with macro cells and small cells. In [183][184] deterministic models and system simulations where considered for evaluating the spectral efficiency of femtocells utilizing FFR as a function of the femtocell's location in a two-tier network with base stations modeled as a hexagonal grid and femtocells uniformly deployed in each cell. The resource allocation scheme in [183] decides the allocation of sub-bands to the femtocells that are not used in the cell area where the femto cell is located. In [185] an analytical evaluation of strict FFR and SFR in a 2-tier network is presented that uses a Poisson point process to model the access point locations. It evaluates the coverage probability and the average rate by means of tractable expressions deriving from the model. More recently, in [186] proposes the optimal static FFR (OSFFR) scheme for a two-tier network. It consists in partitioning the macrocell coverage into the center zone and the edge zone with six sectors in each zone so that reuse 1 is applied in the center zone and reuse 6 in the edge zone of the macrocell. As for the femto cells, a distributed algorithm is proposed that chooses subbands not used in the macro cell sub-area. In general the use of FFR techniques for multi-tier networks is identified as a proper solution because it requires minimal cooperation among base stations and low complex operational mechanisms [186].

An interference management scheme for LTE-Advanced LPNs, called Autonomous Component Carrier, is proposed in [204]. It is a distributed, scalable solution based on minimal information exchange between the nodes. It assumes that each node gathers knowledge from the surrounding environment and uses that information for the decision process. The idea in this paper is the following: they are Primary component carriers (PCC) and Secondary ones (SCC). The PCC is automatically selected by the HNB which are orthogonal to the other PCCs used from other HNBs. The SCCs can be reused from other HNBs by taking into account the interference. The procedure is explained in detail in [205]. Each cell automatically selects one of the component carriers as PCC. Each cell dynamically selects additional component carriers (SCC) for transmission/reception as well (i.e. second step after having selected the primary component carrier). The selection of primary and secondary carriers is done locally by each cell and it uses the following information sources to determine if can be allowed to allocate more secondary component carriers: (i) Radio resource allocation table (RRAT): The RRAT is a table expressing which component carriers are allocated by the surrounding eNBs. (ii) Background interference matrix (BIM): Each cell maintains information on all the potential interfering cells and a corresponding conditional C/I value. The C/I value is a measure of mutual interference coupling between a pair of cells, in case the interfered cell and the interfering cell use the same component carrier simultaneously. The values in the locally stored BIM can be updated either periodically or event based.

In [206] the notion of Background interference matrix (BIM) is exploited again in order for the HNBs to establish their RRM policy. The idea is that when there is a mutual interference coupling between two neighboring LPNs (based on their path loss measurements reported in BIM) then they form a coalition and they estimate the impact of their allocation to the others. The LPNs with strong interference to each other in a specific Component Carriers CC form a coalition on this CC and perform hard partitioning of the resources among them.

An optimum decentralized spectrum allocation policy for two-tier OFDMA networks is proposed in [201]. The paper assumes orthogonal assignment between macrocell and femtocells to eliminate cross-tier interference. For the co-tier interference it proposes a Frequency ALOHA strategy where each LPN accesses a random set of frequency subchannels. Instead of a fixed deployment scenario it uses a Spatial Poisson Process to model the presence and position of LPNs. It calculates the optimal fraction of the total spectrum to be assigned to the macro-layer. The proposed allocation depends on the per-tier throughputs, the loading of users in each tier and the QoS requirements accounting for co-channel interference and path losses.

Power Control for Inter-Cell Interference Coordination

Power Control methods deal with techniques that adjust the power of the LPNs and that differ from the ones used in the macro cells [187]. The control of the power is carried out by taking into account parameters such as the Path Loss of the macro cell users and the LPNs and the power received by a LPN from the strongest interfering macro cell.

Several works have been proposed to optimize power allocation using either centralized or distributed approaches. Most of these approaches propose to reduce the radiated power of LPNs to limit the interference impact on the victim MUEs usually at the expense of a service degradation of LPN users. Centralized approaches take advantage of the hierarchical architecture of the HetNet infrastructure. Power reduction based on backhaul signalling is recommended between MeNBs and between MeNBs and picocells due to the existence of the backhaul interface X2 which can help in guaranteeing bounded delays. However, signaling exchanges between MeNBs and femtocells need better solutions since the communication delays rely on the consumers' broadband connections.

Most proposed power adjustment solutions are based on the signal strength measurements performed locally by eNodeB/MUEs and/or LPN/HUEs in terms of SINR and received signal strength (RSS) and can be classified as follows:

- Strongest received power at HeNB: In this approach, the received power from the strongest co-channel macrocell received by the HeNB is used to adjust the HeNB transmission power. This strategy has the advantage of simplicity since it relies only on the local measurements at HeNBs and does not require specific signalling exchange with the MeNBs [193].
- Pathloss measurements: In these strategies, the power control depends on the measurement of the indoor pathloss and the penetration loss between the nearest MUE and the femtocell.
- Maintaining MUE and/or HUE QoS: In the first category of solutions, the objective is to adjust the radiated power of HeNBs so as to guarantee a target SINR for the victim MUEs that are in the vicinity of interfering HeNBs. Whereas the second category of solutions aims at constraining the HUE users to a minimum tolerated QoS (minimum SINR) by tuning adequately the transmission power of the HeNBs and thus mitigating as much as possible the interference on MUE users. Note that these approaches require SINR and RSS sensing by MUEs or HUEs.

In [194], [195], uplink power control schemes have been proposed. A distributed utility-based SINR adaptation was proposed in [194] to alleviate the cross-tier interference caused by the affecting femtocells. The authors in [195] studied two interference mitigation strategies to adjust the maximum transmit power. In a similar way, power control scheme for the DL for an integrated femto and macro cell network was studied in [196] while considering the minimum SINR of both MUEs and HUEs.

Other solutions consider jointly power control, resource allocation and handover strategies. In [198], an Intra-cell Handover (IHO) approach was proposed in which MUEs or HUEs have the ability to be transferred from one subchannel to another in case of interference or fading, if a free or a better sub-channel is available in their serving cell. A second scheme is proposed as a centralized downlink power control procedure executed by the MeNB, which uses the RSS to measure the interference. This scheme helps in alleviating the interference, but generates important signaling since each sub-frame allocation should integrate a new command to every interfering femtocell. Besides, the interfering femtocell should have a good knowledge about the sub-channels which are used by the MUEs in the DL.

In [197], a Hungarian algorithm is used in a joint power control and resource allocation scheme for a co-channel assignment. The interference in DL is mitigated while satisfying the QoS required by MUEs in both centralized and distributed cases. The distributed scheme imposes some coordination and message exchanges between cells to indicate the interference level at both macrocell and femtocell sides. In [199], a hybrid spectrum resource coordination for the two-tier macro-femto cell system is proposed. In this technique, the MUEs return a report specifying the Reference Signal Received Power (RSRP) of their serving cells and all existing nearby HeNBs.To reduce the signaling overhead, two different messages reflecting the arrival and departure of an MUE are used. When the MUE switches form Active to Idle mode or its RSRP is greater than a predefined threshold, a Measurement Report (MR) is sent. Note that in this method the HeNB does not act on the transmitted power, it tries instead to reallocate the Resource Blocks (RBs) of the MUE victims.

In [207] a distributed inter-cell power allocation algorithm is proposed where each cell computes by an iterative process its minimum power budget to meet its local QoS constraints based on a three-regime interference classifier. The idea is the following: when interference is low it is treated as noise, when it is higher both the interferer and the correct signal are decoded. When the interferer is too high then first decode the interfering signal with the information signal as noise and then subtract the interference from the information signal.

As already mentioned one of the most challenging interference scenarios in two-tier networks is the radiated power of LPNs to victim macrocell users in the case of shared spectrum and closed access LPNs. One approach to address this type of interference is to apply on the LPN a power control mechanism based on the detection of 'victim' UEs in the area. In [208] a downlink power control algorithm was proposed. The objective was to provide protection to a "victim" MUE against LPN downlink interference while maintaining acceptable LPN performance. In order to detect the victim MUE, monitoring of the uplink channel by the LPN was proposed. When a co-channel MUE is detected, the LPN adjusts its power in order for the MUE to keep an acceptable predefined SINR target.

In order to highlight the potential gain of using richer context information stored in a REM, this algorithm was modified in [203] by taking into consideration rich environmental information for the deployment area. Complete knowledge of the network components locations, the path losses and shadowing terms was assumed. This information was used for the accurate calculation of the HeNB transmit power and it was compared with the baseline algorithm of [208]. The performance metric was the outage experienced by the "victim" MUE when it cannot meet its SINR target because of the HeNB interference. The presented performance gain was essentially an upper bound for pragmatic context-aware algorithms, considering that the inaccuracies in the stored data will result in reduced performance. While the location of eNBs can be assumed to be known advance, the HeNB locations need to be estimated since the users may place them randomly inside the house. The victim MUE position relative to the HeNB and the building also has to be estimated. The path loss term for the calculation of the channel gains between the network elements is also assumed to be stored in the REM for a specific area based on operator measurements. A dedicated sensor network can be used to estimate the detailed propagation characteristics of a specific environment, but this also may result in inaccurate or outdated estimates.

User-to-cell association

As already referred, the introduction of the lower power nodes (LPN) to the network infrastructure is followed by some challenges that need to be faced. The main problem comes from the interference that in this case is more difficult to be controlled. For example, femto cells are deployed in an operator unplanned manner; as such, the operator is not aware of the number of the existing nodes as well as of their location. This makes the usage of the already existing interference management techniques insufficient, and poses the need for more advanced schemes. Moreover, the CSG mode that some femto cells may operate, introduces additional interference problems. Users connected to a CSG femto may generate and/or receive interference from unauthorized users which are forced to be connected with a macro cell with which they may not experience high quality transmissions [163].

Another important challenge emerges from the different characteristics of the LPNs and the macro cells. In addition to their smaller size, LPNs also present a significant difference in the power levels they transmit. As already referred in the previous chapter, typical values for a pico cell are between 250mW and 2W, while for a macro cell these values can be in the order of 40 W. Furthermore, the LPNs are equipped with antennas of lower gains and in lower heights, which may result in higher path-losses. The combination of the above mentioned issues leads the LPNs to provide smaller coverage areas, thus to serve less users. Since the available bandwidth is equally shared among the macro cell and the LPNs the capacity is unevenly distributed [188].

In order to compensate the traffic distribution and consequently to offer capacity fairness, a user association technique is used, known as Cell Range Expansion (CRE) [189], [190]. In traditional network deployments, the user association is carried out according to the measured RSS. In HetNet deployments, this approach is not always optimal, since LPNs might not be fully loaded. With CRE, the users can connect with LPNs even if the RSS is lower (up to a certain extent) than that of the macro cell. This is carried out by using a cell bias that depends on whether a cell is fully loaded or not. In particular, when the cell load is light a positive offset is introduced in the RSS measurements of the LPN users during cell association [159]. This results in the increment of the LPNs footprint, and hence the name *Cell Range Expansion* (Figure 2-7).

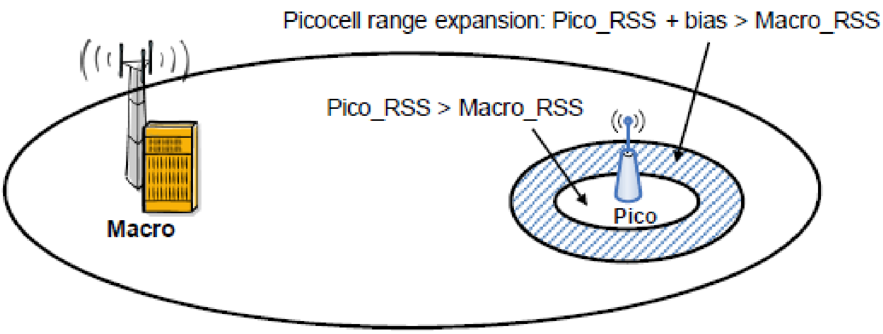

Figure 2-7: Cell Range Expansion [191]

Despite the fact that CRE performs well in the case of the inter-cell interference, the users in the cell borders experience low signal quality, thus they are very susceptible to interference from the macro cell. As such, research is ongoing on the optimization of the particular scheme. In [191], the authors proposed an interference coordination scheme that makes use of a set of resource allocation rules. The scheme performs joint coordination of power and frequency in order to reduce the outage rate and boost capacity of the system. Moreover, in [192] dynamicity has been introduced to the CRE through the adaptation of the cell bias depending on the network environment. Simulation results have shown improvement in the edge users performance compared to the static schemes, while maintaining the overall network performance.

In [209] a capacity analysis is performed of a hetnet that combines both interference coordination through blank subframes and cell range expansion. For the parameters considered in the paper it is observed the gain that interference coordination achieves for different values of the range expansion bias. However, the paper does not focus on establishing the best configuration of these parameters and the evaluation is performed in a regular scenario with all the small cells at the same distance of the macrocell. In [210] the problem of user-to-cell assignment by modifying the range expansion bias is analysed. Both uplink and downlink are considered and the objective is the minimization of the cell load, for which a game theory approach is proposed. Similarly, [211] formulates the user-to-cell association problem taking into account fairness and SINR considerations. A solution based on linear programming is proposed, together with a greedy algorithm. In [212] the optimization of the user to cell association is performed to achieve load balancing in a hetnet. A low complexity distributed algorithm that converges to a near-optimal solution is proposed, and it is observed that its performance can be very well approximated by a simpler per-tier biasing approach, provided by the bias values are carefully chosen.

The joint optimization of the user-to-cell association through CRE and the time-domain interference coordination through ABS has been only very recently considered. Specifically, in [213] the proposed formulation considers the amount of ABS left by the macrocell and the value of Cell Selection Bias (CBS) to maximize the user throughput. It is established that computing the optimal solution is computationally hard so an efficient algorithm to compute ABS and CBS is proposed, that performs within 90% of the optimal.

2.3.4 Shared use of spectrum in HetNets

A relevant candidate solution for dealing with the frequency assignment in Hetnet scenarios can be the use of spectrum sharing approaches. The shared use of spectrum refers to situations in which a number of independent users and/or devices are allowed to access the same range of frequencies under certain conditions [217]. Spectrum sharing models can be categorized based on the following characteristics [218]. The first step is to determine whether sharing is based on cooperation or coexistence. In a model based on cooperation, systems or devices sharing the band must communicate and cooperate with each other to avoid mutual interference. With a coexistence model, devices try to avoid interference without explicit signaling (at most, devices sense each other's presence as interference). A second step is to determine whether the spectrum-sharing arrangement comprises primary-secondary sharing or sharing among equals. In the former case, some systems have the right to operate as a primary spectrum-user, and policy mandates that secondary devices are not allowed to cause harmful interference to a primary system. In the latter case, all devices have equal rights, and typically there is more flexibility about how to behave in the presence of peers.

Spectrum sharing model does not directly define the licensing conditions. E.g. in a primary-secondary sharing model where TV broadcasters are primary users, secondary access could be enabled either under license-exempt conditions to short range devices or exclusive license conditions granted to e.g. a cellular operator in a more or less dynamic way. As a result, in the context of a HetNet scenario, with a high number of small cells transmitting at low power levels, having reduced coverage areas, and exhibiting high fluctuations in the traffic demand depending on the time/places, spectrum sharing can be an efficient solution to be explored, as long as it does not require the acquisition of permanent licenses.

Most efforts currently underway to allow the exploitation of unused spectrum on a secondary basis are focused on the frequency band from 470 MHz to 790 MHz mainly used for TV broadcasting (i.e. TV white spaces). In this respect, the general consensus among regulators (Ofcom – Office of Communication, FCC – Federal Communications Commission and Commission of European Post and Telecommunications (CEPT's) Spectrum Engineering (SE) 43 working group), is that in the short term the use of geo-location databases is the technically most feasible approach to exploit TVWS since currently sensing techniques, employed by stand-alone devices either cannot guarantee reliable detection of primary systems or require expensive cognitive equipment. Also, there seems to be a general consensus that implementation of secondary sharing based on beacons is problematic due to the required infrastructure that needs to be in place and maintained.

US regulation still advocates for a license-exempt regime for spectrum authorisation to White Space Devices (WSDs). Also, regulations do not impose restrictions on the applications and technology used by WSDs. This turns into many interesting uses cases that can benefit from the use of TVWSs such as hotspot urban Internet connectivity, wide-area or rural Internet broadband access, wireless backhauling, rapid deployed networks, indoor networking, etc.

Nevertheless, license-exempt use of TVWS spectrum through geo-location databases is not the only approach to consider. COGEU project [219] has proposed the management of TVWS through a spectrum broker that supports real-time spectrum trading of TVWS spectrum bands [220]. Similarly, another key approach to secondary use of spectrum is the Authorized Share Access (ASA) model initially proposed by industry players like Nokia and Qualcomm [221] and the further extension of the concept to the so-called Licensed Shared Access (LSA) [222].

LSA/ASA allows for long term exclusive license or spectrum reservation in a given region for secondary users on a shared and non-interference basis. Hence, it is intended to enable licensed use of spectrum for mobile services with predictable quality of service at specific periods of time. Relative to license-exempt, LSA/ASA can have benefits for sharers and incumbent users, given that the incumbent will not receive harmful interference and the sharer can receive assurance over the level of capacity and the operating conditions in the band, which can help in providing predictable QoS assurances and thus in extending the range of spectrum available for mobile broadband use. Sharing conditions between incumbents and LSA/ASA licensees may be static (e.g. specific exclusion zone or time allowed for operation) or more dynamic (e.g. geographic/time sharing, on-demand authorisation by LSA/ASA licensees or on-demand restrictions imposed by incumbents). Dynamic implementation of LSA/ASA could take advantage of the recent advances in cognitive technology, allowing spectrum sharing on a frequency, location and time sharing basis. However, in the case of the incumbent(s) imposing restrictions, a system for updating, maintaining and providing the access conditions would first need to be established.

Among the expected usage scenarios for LSA, [222] identifies the bandwidth expansion for a mobile network operator as a relevant use case. In this use case, an LTE mobile operator in a licensed band applies for an individual authorization to use frequencies within the 2300 - 2400 MHz band to use a portion of this band under the LSA regime. The application for authorization may include the geographical region and the time period in which the mobile network operator plans to access this portion of band. The administration/National Regulatory Authority determines with relevant stakeholders (i.e. incumbent user and mobile operator) the conditions of the LSA sharing framework. Conditions to use the spectrum may be made available in an information repository that may be accessed by the mobile operator's OAM (Operation, Administration and Maintenance) system, so that at the appropriate time the relevant base stations are enabled transmission in the allowed portion. When the granted time period expires, the base stations are instructed to disable transmission in the allowed portion. The LSA usage for small cells becomes a particularly relevant example in the above scenario, because of the low transmit power of small cells and their small coverage areas, which provides a smaller geographical granularity. This allows a small cell deployment to better fully cover an authorized geographical area under the LSA regime, and so create the opportunity of sharing in areas where macro cell deployments would not be possible due to the likely absence of the TVWS large coverage area availability, such as downtown in big cities, etc.

Spectrum trading could be one enabler for efficient spectrum sharing and is expected to enhance competition by making it easier and faster for market entrants to gain access to spectrum. According to Ofcom's definitions provided in [223], spectrum trading denotes the ability to sell and buy access to radio spectrum within the overall terms of the original assignment. In theory, spectrum trading could be done across varying time-frames, from years or decades as the original auctions held by regulators dictate, or weeks or months as emerging spectrum trading houses currently facilitate or down to the order of minutes or seconds. While working with spectrum trades that operate on monthly or weekly periods can readily be performed by humans, trading spectrum on a lower timescale requires a more automated approach. In this context, the QoSMOS project has studied spectrum micro-trading for mobile operators as a means of improved spectrum efficiency [224]. Spectrum micro-trading can be defined as the possibility to buy and sell spectrum resources on a small scale in the spatial, temporal and frequency dimensions. This would enable wireless services to acquire spectrum for small or wide geographical areas, for short or long time periods and for narrow or wide bandwidths. Hence, spectrum utilization and the opportunity to acquire spectrum resources might increase when optimizing metrics and specifying market policies properly. In [220] the concept of spectrum broker for implementing spectrum trading of TVWS is presented. The broker allocates the spectrum for short term disposal making use of trading mechanisms and acting either as merchant mode or auction mode depending on the relation between spectrum offer and demand.

Work by Buddhikot [225] also provides some considerations on the realisation of real-time secondary markets. It distinguishes between homogeneous and heterogeneous multi-operator sharing via real-time secondary markets. In the former approach, users participating in the secondary market are offering the same type of services (e.g. commercial cellular services). In the latter approach, secondary market participants are providers of different services such as cellular, public safety and TV broadcasters. In order to implement such approaches, a potential solution framework could consist of a centralised mechanism in the form of spectrum coordination server (or spectrum broker) which communicates with participant operators to take care of spectrum access requests, assignments and reversions.

Different works have recognized recently the potentials of applying spectrum sharing to small cell scenarios. In [226], it is discussed how to apply CR technology for expanding LTE spectrum and presents a CR prototype for LTE TDD to demonstrate the feasibility of dynamically utilizing TVWS spectrum. Moreover, the application of CR to small cell scenarios is identified as a relevant use case to enhance the capacity while at the same time avoiding co-channel interference between adjacent small cells and between the macrocell and the small cell. In [227], the commercial viability of secondary spectrum access in different scenarios is assessed. It is concluded that, due to aggregate interference considerations that reduce the availability of TVWS, it is difficult to find suitable reuse locations to achieve a contiguous macrocellular coverage based on TVWS. Instead, the use of TVWS as a microcellular capacity booster in limited local areas is seen as a more plausible approach. A similar conclusion is obtained in [228], where the suitability of TVWS bands for use by cellular network is analysed. It is found that, due to the high interference from TV towers, it is difficult to find channels that allow a good performance of cellular networks such as LTE at the cell edge, while the inner part of the cell can obtain more benefits from TVWS. As a result it is concluded that TVWS is primarily suitable for traffic offloading and spotty coverage (as it would be the case of small cell networks) rather than for building large contiguous coverage networks. In [229], the deployment of a cellular network in TVWS is analyzed, deriving a methodology to maximize the downlink capacity at the cell edge of base stations using a heuristic power allocation algorithm. It is concluded that only through dense cellular networks (i.e. small cell sizes that require low power levels) it is possible to efficiently exploit the secondary spectrum.

The possibility of extending LTE in the TVWS band has also been considered in [230] where two joint RRM algorithms are proposed to assign resource blocks to either legacy carriers or to carriers in the TVWS band which are allocated by a spectrum broker. However, the evaluation is only performed in a macrocellular scenario. The operation of the spectrum broker that assigns TVWS bands is presented in [231] considering the problem of matching multiple-bids to buy, and band portfolio to sell as offered by a spectrum broker, and proposing two heuristic algorithms. In turn, in [232] an auction approach for using TVWS with LTE and LTE-A is proposed. Resource allocation is modelled as a combinatorial auction with heterogeneous objects and profit maximization allocation rule.

In [233] the use of TVWS is proposed to deal with interference mitigation in LTE femtocell networks, in particular the interference suffered by macrocell users from nearby femtocells. The proposed approach is based on a cognitive sensing stage in which the interfering femtocell list is identified and a resource allocation stage in which the TVWS resource blocks are allocated to these interfering femtocells based on TVWS availability. In the context of the SACRA project [234] the joint operation of licensed LTE bands and TVWS bands used opportunistically has also been considered. The proposed framework is mainly based on rules and policies for resource usage across bands for protecting primary users that impact on the sensing configuration and the secondary access control. In the framework of the FARAMIR Project, among the different considered optimization problems in [235], the allocation of TVWS to LTE-based femtocell access points is addressed. A one map-colouring algorithm is used for allocating spectrum to the femtocells, together with a power optimization algorithm based on simulated annealing.

2.3.5 Game-theoretic energy-efficient control and resource allocation algorithms in HetNets

Distributed energy-efficient power optimization in cellular relay networks

The ever-increasing demand for high-speed ubiquitous wireless communications calls for efficient solutions in terms of energy expenditure and bandwidth occupation [240]. Among others, *relay-assisted communication* has become a very promising technique in a number of wireless systems, such as ad-hoc, mesh, and cellular networks [241], [242], [243], [244], [245], [246]. For instance, the usage of relays in a cellular system is a topic of study in 3GPP's LTE [247] and has recently been standardized in the IEEE 802.16j standard [248].

In the context of cellular communications, relays are dedicated network elements, placed at certain locations in the cell (either planned or unplanned, and either fixed, mobile, or nomadic [249]) to help forwarding the transmitted message from (to) the base station to (from) the user terminals in the downlink (uplink). Much research effort has been devoted in the last three decades to understand and to assess the benefits of cooperative relaying in wireless communications.

The reasons why relay-assisted communications have been gaining momentum both in the industry and in the academic world are given by a number of potential advantages. The most appealing feature is the capability, through effective resource sharing in the network, to *improve coverage, throughput, and reliability of the communication* in terms of quality-of-service (QoS) and blocking probability [246], [249], [250], [251], [252], [253], [254], [255]. Relays provide in fact power gains due to the reduction of distance-related attenuation in coverage-limited scenarios [256], [257]. Another feature of cooperative relaying is its potential to *mitigate inter-cell interference* (ICI) at the cell edges. Message relaying helps connecting the base station with the terminals of edge users, at the same time limiting the interference created to the other users of neighboring cells [254]. Such a solution is also *cost-efficient* [249], since it avoids the backhaul costs involving data aggregation as well as infrastructure costs associated with backbone connectivity, thanks to the use of the air interface [254]. A further key issue that suggests the introduction of relaying operation is the significant *energy saving* that may be obtained in relaying, owing to the use of transmit powers lower than those required to reach the destination in the direct link [[242], [255]]. Reducing the peak power emitted by a base station may reduce the cost of radio frequency power amplifiers and hence capital expenses for deploying cellular networks [254].

Despite the huge literature on the subject, there are still many open problems in the design of relay-assisted communications. For instance, many relaying schemes are based on a centralized controller, which allocates the radio resources among the network units. Since perfect channel state information (CSI) between sources and destinations, and between sources and relays, is required to solve the maximization problem, the radio resource management (RRM) is performed in a centralized fashion [254]. This bears a number of negative aspects. First, *scalability* of centralized algorithms is severely reduced, as the optimal allocation is typically a NP-hard problem. This prevents us from extending the proposed algorithms to operational scenarios with hundreds to thousands of terminals per cell, thus reducing the industrial appeal and the applicability of such methods. Moreover, collecting the information at a common concentration point may significantly reduce the network throughput, due to the bandwidth drained by feedback channels. Also, the very assumption of availability of perfect CSI is questionable in time-varying environments wherein channel estimation may become problematic.

Other issues that are often overlooked are (i) fairness/QoS management [249], [254], and (ii) energy efficiency. In next-generation networks different classes of users will coexist, so that it is fundamental to manage different traffic constraints while dealing with location and channel conditions. This can be done only by apportioning the available resources (power and bandwidth) in a very efficient way among the elements of the network, so as to monitor global network performance. Concerning ii), wireless networks are populated by battery-powered mobile terminals, whose performance in terms of throughput must be traded off with power consumption, which limits batter life. In many applications, even relays will be battery-powered, as in the case of nomadic or mobile relay stations [249]. Extending the lifetime of such networks becomes a crucial aspect to maintain the data exchange uninterrupted. Finally, most available literature on the general topic of relaying and resource allocation is focused on a simple single-cell scenario. In more realistic multicellular systems, it is of paramount importance to consider the effects of resource allocation for relay-based networks that adopt frequency reuse, by also exploiting the high degrees of freedom provided by routing and scheduling protocols, and by relay selection and placement.

Distributed energy-efficient power optimization in HetNets

Wireless communication links, systems and networks are designed to transmit the highest achievable information rate for a prescribed QoS, or to obtain the highest possible QoS for a fixed information rate to be transmitted. In a multiuser context, this task is mainly accomplished through dynamic radio resource management, wherein the dynamic assignment of the radio resources (e.g. time slots, frequencies, space dimensions, power) enables the maximization of the chosen utility functions for multiple users simultaneously active in the network. Green radio concept calls for novel radio resource management techniques incorporating the cost of energy in the performance metric. Towards this goal, the concept of link capacity per unit cost has been originally proposed by [261], and successively extended for different wireless systems targeting the maximization of the number of bits/sec reliably transmitted per energy unit (see for example [262], [263], [264]).

Over the last years, intense research activity has been devoted to the design of wireless devices capable of self-enforcing the negotiated agreements on the resource usage. Not surprisingly, the natural theoretical tool for designing decentralized strategies in such scenarios has been identified in game theory. In [265] the authors proposed an accurate analysis of the Nash equilibrium point for a group of wireless devices targeting the maximization of their individual spectral efficiency in parallel Gaussian multi access channels. In this scenario, mobile users can autonomously take decisions on the resource usage and compete with each other to exploit available radio resources. This distributed decision process has the great advantage of avoiding waste of energy due to the excessive information exchange required to achieve signal coordination as well as involved processing at the base station. On the other hand, users' aggressive attitude toward interference can lead to large transmission power at the mobile stations, thus fostering an inefficient use of the batteries. More recently in [264] the authors have investigated the same scenario and analyzed the Nash equilibrium problem for a group of players aiming at maximizing of their own energy efficiency. However, in [264] the authors do not provide a systematic study on the relationship between the rate and energy-efficient maximization equilibrium points. The need of a better understanding on the way the two different requirements are related to each other is what motivates this research activity. In particular, one of the objectives of this work is to demonstrate that rate and energy-efficient maximization are two instances of a properly defined generalized Nash equilibrium problem whose utility functions are the users' rates. Under this perspective, the existence and uniqueness results for the generalized Nash equilibrium remain valid for all the possible instances of this more general game. All this is achieved by means of the quasi-variational inequality (QVI) framework introduced by Bensoussan in [266] as a modelling tool capable of describing equilibrium situations in different fields such as generalized Nash games, economics, and biology (see [267] and reference therein). Unlike the traditional variational-inequality (VI) problems, which have an extensive literature also in the field of wireless communications (see [268] for example), contributions devoted to the numerical solution of QVIs are relatively recent [293].

Distributed energy-efficient power optimization in BICM-OFDM systems

The type of scenario under investigation affects the design of a RA algorithm. In point-to-point or point-to-multipoint communications there is usually an element of the networks that is aware of all the necessary information to perform the RA algorithm; this is referred as centralized RA. Multiple Access Channels (MACs) or multipoint-to-multipoint communications on the other hand, are usually characterized by multiple links sharing a common communication medium and interfering with each other. In this case, the design of distributed RA algorithms is preferable and game theory [275] emerges as the most suitable tool to describe such kind of scenarios. In the following, a brief summary on the main link adaptation and RA algorithms for energy-efficient communications is presented. The focus is on the literature related to game theoretic approaches.

Centralized energy-efficient link adaptation and RA algorithms

The seminal work done in [261] investigates the energy efficiency (EE) of Soft Input Soft Output (SISO) additive white Gaussian noise (AWGN) channels under a theoretical point of view, i.e., assuming infinite length Gaussian codebooks. According to this work, the EE function is the capacity per unit cost (bit/s/Hz/J), which is maximized when the system transmits with a very low power, and thus with a very low data rate. In [262] the problem of finding the optimal precoding for MIMO systems over slow fading channels is investigated, considering infinite length Gaussian codebooks and CSI only at the receiver. The goal is to optimize the EE in terms of goodput-to-power ratio, where the goodput is given by the product between the chosen data rate and the complementary of the outage probability. Although several open issues are left, interesting results on the optimal precoding are analytically assessed for the cases of one single antenna at Rx, for low SNR and high SNR regime and for the case of uniform power allocation when large number of antennas is considered.

From a pragmatic point of view, [276] investigates a point-to-point communication system, characterized by an AWGN channel, where both uncoded and coded QAM modulations and MFSK modulation are employed. The aim is find the number of bits per modulation symbol that minimizes the energy consumption per information bit, taking into account both transmission and circuit energy consumption as well as the transmission time. The latter is in particular a function of the bit error rate (BER), evaluated via error-bound approximations.

[277] proposes an efficient algorithm based on geometric programming that finds the pair BER and bit-per-symbol that minimize the energy per successfully received bit (good bit) for an ARQ based QAM system over AWGN channel. The same authors in [278] tackle also the long-term frequency flat fading case, offering a sub-optimal iterative algorithm, where, at each step, the optimal bit-per-symbol for a given BER value and the optimal BER for a given bit-per-symbol value are evaluated. Also here, the circuit energy consumption is considered.

In [279], the problem first analyzed in [276] is extended to a packet-oriented transmission system over fading channels. The optimization metric, i.e., the energy consumption for successfully received bits is a function of the frame success rate (FSR), which in turn depends on the modulation order, frame length and the mean SNR. Both the cases of static and i.i.d. fading among different retransmissions are considered. The authors first derive the optimal mean SNR as a function of the distance between the transmitter (Tx) and receiver (Rx) for a given modulation order and frame length. Then, it is shown that the optimal modulation size that minimizes the energy consumption for successfully received bits grows as the distance between the Tx and Rx decreases.

Authors in [280] propose a novel metric, for an OFDM link, defined as “throughput per Joule”, that is the ratio between the sum of the transmission data rate (evaluated as the capacity with SNR gap to account for the discrete modulation and coding scheme employed) over the subcarriers and total power consumption, given by the sum of the circuitry power and the required transmission power. The proposed link adaptation consists in finding the optimal data rate vector that maximized the EE efficiency with a constraint on the minimum data rate.

Distributed energy-efficient RA algorithms

Fundamental works in this context can be found in [296] and [281], where the authors tackle the distributed power control (PC) problem in multiple access flat fading wireless data networks. The EE of each terminal is evaluated as ratio of the transmission rate times the frame success rate (FSR) and the transmission power. The problem is recast into a non-cooperative game where the terminals, the set of feasible power values and the EE functions, represent the set of players, strategies and utility functions respectively. Authors first show the existence and uniqueness of the Nash equilibrium of the game. Interestingly, they demonstrate that, at the equilibrium, the optimal PC strategy of each terminal is such that the SINR at all the receivers are equal to an unique value, provided that all users have the same modulation and packet size. Then it is shown that the equilibrium point is inefficient with respect to a PC strategy obtained either through cooperation between terminals or a centralized PC algorithm. To overcome this drawback, in [281] a pricing mechanism is proposed, where the utility function of each terminal is modified by a price that is a linear function of the power. The game with the modified utility functions is then modeled as a supermodular game [282] and a novel distributed PC algorithm is derived, which improves the efficiency of the solution with respect to the case without pricing mechanism. Other approaches aimed at improving the efficiency of the NE of the non-cooperative PC game have been proposed in [283] and [284]. In particular, in [283] a hierarchy in the PC game is introduced in two ways. In the first, a user of the game is chosen to be the leader and the others are the followers. The PC game has then a Stackelberg formulation [282] that, due to the random choice of the leader, may not be optimal. The second approach exploits a successive interference cancellation mechanism and thus introduces hierarchy at the receiver side according to the decoding order of the users. Both approaches show improvements in the EE of each user, compared to the non-cooperative PC game, and, in the second case, the existence and uniqueness of an NE is always guaranteed. A different idea is proposed in [284], where the efficiency of the PC game is improved resorting to a repeated game. Within this framework, several appealing properties hold: first, only individual channel state information (CSI) is required at the transmitters; under sufficient but reasonable conditions the game is PO and is more efficient than that obtained with the Stackelberg game proposed in [283].

In [285], authors investigate the same scenario of [281] but considering direct sequence code division multiple access (DS-CDMA) terminals. The FSR has still a sigmoidal shape since modulations such as BPSK are taken into account. Thus, formally, the non-cooperative PC game is the same than in [281] and the existence and uniqueness of the NE is provided. Moreover, the optimal power allocation (PA) expression for the matched filter, the decorrelator and the minimum mean square error (MMSE) detector are derived. Finally, the comparison with the PO solution and the extension to the multiple-input multiple-output (MIMO) case, where the analysis done for the single-input single-output (SISO) systems readily extend, are proposed. In [286], authors propose a joint rate and PC game for the same scenario described above, adding QoS constraints. Specifically, a minimum average rate and a maximum delay are guaranteed to each user. Conditions on the existence and Pareto optimality of the NE for this game are derived as well as an admission control mechanism. The work done in [287] expands the EE problem tackled in [285] to multicarrier CDMA systems. Considering equal transmission rates for all user, the EE is given by the ratio between the sum of the successfully transmitted rate over each subcarrier and the required transmission power. The non-cooperative game thus returns as NE the set of PA vectors, one per user, such that none of them can unilaterally improve its utility function by choosing a different PA vector. Depending on the channel conditions of each user, this equilibrium can be unique, there can be more than one or cannot exist. As in [285], the equilibrium, when it exists, corresponds to the condition where the SINR at all the receivers are equal to an optimal value. Moreover, this condition is met when each user allocates power only over its “best” subcarrier. In this case, the “best” subcarrier is the one that requires the lowest amount of power to achieve the optimal value. Thus, for such a scenario, the PA game corresponds to a PC game and the authors propose an iterative distributed PC algorithm based on each user's best-response to reach the NE. The EE problem for MAC in CDMA wireless networks is also considered in [288] in a cognitive context. Specifically, secondary, i.e. unlicensed, users (SUs) transmit over the same frequency occupied by primary, i.e. licensed, users (PUs) and the interference caused by the secondary network to the PU must be kept under a prescribed threshold. Two non-cooperative PC games are thus formalized; both aiming at maximizing the EE of each SU, subject to the interference constraint on the PUs and to a fairness constraint on the SUs received powers. In the first PC game the optimization is done only with respect to the transmit power of each user, whereas in the second game, it is done with respect to the transmit power and the choice of the uplink linear receiver. The existence and uniqueness of the NE for both games are analytically assessed. Then, resorting to the large system analysis [289], authors derive a one-shot distributed PC algorithm, where the NE is reached without the need of iterations among the users.

As evident, the majority of the works on EE are based on CDMA whereas very few consider the MAC for OFDM systems. In this field, authors in [280] consider an MAC with OFDM terminals and capacity achieving codes. The EE of each terminal is the sum of the capacity obtained by each subcarrier over the sum of circuit and transmission power. The non-cooperative PA game is investigated and the existence and uniqueness conditions are analytically derived, along with an iterative distributed algorithm to reach the NE of the game.

In [290] an in-depth analysis of the EE in the uplink of multi-cell OFDMA systems is proposed. The EE function of each user, differently from [280], is obtained by summing the EE function of each subcarriers assigned to the user. That is, it is the sum over the subcarriers of ratio between the capacity and the transmission power of each subcarrier. Authors first investigate the non-cooperative PC game where each user tunes its transmission power to maximize the above-mentioned EE function, given a fixed subcarrier allocation. It is shown that this game admits a unique Nash equilibrium. Then, authors investigate the problem of joint subcarrier and power allocation for the scenario at hand. In order to tackle this problem, which is more involved, the EE function is properly modified so that the joint subcarrier and PA game can be recast into a potential game [282].

2.3.6 Hybrid HetNet LTE – M2M Network concept and challenges

Machine-to-Machine communications (M2M) are defined as a form of data communications which do not need human interaction. While the number of human users of mobile networks is coming to saturation, the M2M domain is seen as a new revenue opportunity. In general, the estimates agree that the number of M2M connections will grow in the coming years [307]. Market researches such as [309], [310] predict up to 800 million machine to machine (M2M) connections by 2015, while standardization organizations argue for very high densities of M2M devices in broadband bandwidths [311]. Mobile operators like Telnor, Vodafone and Telefonica have created dedicated units or even companies to focus on M2M business opportunities. Similarly, mobile vendors are creating their own visions, such as the Ericsson's "50 billion connected devices". Large IT vendors like IBM or HP also have ambitious plans to connect and exploit information generated by trillions of sensors. Enhancing M2M with cellular connectivity is expected to be crucial for the success of the M2M ecosystem. Cellular networks are expected to provide ubiquitous coverage at low deployment costs, and this is why significant effort has been lately devoted by standardization organization. The 3rd Generation Partnership Project (3GPP) has formed several Machine Type Communication (MTC)-related study items working on M2M enhancements for future releases [312]. IEEE has initiated the 802.16p and 802.16.1b projects dealing with M2M amendments on Mobile Wimax standard [313]. ETSI has been working on defining M2M functional architecture and interface specifications through an M2M Technical Committee [314].

A number of important differences have been identified in literature between Machine Type (MTC) and Human to human (H2H) communications. MTC involves several entities which do not necessarily need human's operation. The main use cases have been identified in 3GPP Technical Report 37.868 [297]. Those uses cases are metering, road security, and consumer electronic and devices. Taking those cases as examples, it is clear that the main differences from H2H communications are: (i) different market scenarios, (ii) supported services: unlike traditional H2H services, such as voice and web streaming, M2M services often have very different requirements due to their specific feature (e.g. group-based communications, low or no mobility, time controlled operation, delay tolerant, small and infrequent data transmission, secure connections, MTC monitoring, priority alarm messages, extra low power consumption, high reliability, etc.), (iii) lower cost devices, (iv) a very large number of types of end devices, (v) little traffic from every device. These differences dictate the need for the 3GPP standards to be revisited and adapted to support the advent of this new technology.

The open literature on the topic is not so extensive. A European project on the topic is the ICT project EXALTED (Expanding LTE for Devices). The project targeted towards developing a new architecture to support efficient and cost-effective wireless M2M communications. In the following paragraphs, the most significant contributions in literature will be presented, including the EXALTED project, along with the identification of the main research problems.

The problem of low cost LTE devices is a first challenge to be tackled, and it is already a priority for 3GPP in the context of RAN1 group. A notable contribution can be found in [298]. Few schemes have been recently proposed to deal with the multiplexed access of machines to the e-UTRAN network, such as [299], [300]. The way to handle multiple kind of traffic and guarantee the heterogeneous QoS requirements is an open issue, which has been tackled in few contributions (e.g. [301]). A study on latency requirements and bottlenecks across the whole architecture is given in [302]. In [298] a contribution compliant with the signaling standard of 3GPP release 10 is proposed. In general, for the problems discussed above, the scheduling algorithms proposed for generic LTE systems based on H2H communications cannot be reused for MTC. In [299] the authors propose a grouping-based technique for LTE-A stations to manage radio resources for MTC devices, according to which they form clusters with respect to their packet arrival rate and maximum jitter. Channel quality is not considered here, whereas it is considered in [300] where two uplink scheduling schemes are presented, taking into account the channel conditions and the maximum allowed delay of each device that requests transmission. In [303] a semi-persistent scheduling scheme is applied to VoIP traffic, which presents similar characteristics to the MTC. In particular, LTE is supposed to support hundreds of VoIP users that generate small amounts of periodic data traffic. In the literature, semi-persistent scheduling schemes have been proposed to deal with this special traffic characteristic [303], as they make allocation decisions for a longer time period than usual, thus making it unnecessary to inform the UEs on a Transmission Time Interval (TTI) basis. An overview of scheduling for M2M traffic over LTE state of the art is provided in [304], while a performance comparison between three delay-aware scheduling algorithms for M2M traffic over an LTE system is given in [305].

A related issue is also the problem of how to efficiently handle the access to the random access channel (RACH) when the number of users scales significantly, as it is the case for M2M. To address that, several solutions have been studied including time controlled access, staggered access, overload indicators to prevent MTC devices from access attempts, etc. In the RA process, the UE shall go through a preliminary stage, called Access Barring Check (ABC), where the UE should check whether the access to the network is prevented or not, based on the received System Information and its random-generation number. Once passed the ABC procedure, the UE starts transmitting a preamble to the eNB, which will be the actual load to the RACH. In 3GPP it is still an open issue how to design the ABC mechanism, and some proposals can be found in literature. Some preliminary work can be found in [306]. A more mature proposal is presented in [307], where two most probable candidate methods for RA preamble allocation and management are discussed for LTE-A network protocol. The first method proposes to completely split the set of available RA preambles into two disjoint subsets, one for H2H customers and the other one for M2M devices. The second method again splits the set into two subsets, but while one of the two sets is devoted to H2H communications, the second one is split for both H2H and M2M customers. In [308] a novel congestion scheme, which takes advantage of existing congestion schemes, is proposed to curb the severe congestion problem and reduce the impact on QoS of existing H2H devices.

Another important line of research is to evaluate the actual impact that the coexistence of M2M and H2H communications would have on a LTE network. In [304] this is studied by means of a Markovian model, which is parameterized by laboratory measurements and ray tracing simulations. In [305] coverage and capacity analysis for Machine type communications in LTE are analyzed. Another important issue is the coexistence in the same band of M2M and H2H traffic. This generates a difficult to scale interference problem. Some work on this is initiated in [303].

2.3.7 Summary of open issues

Based on the above analysis it follows a summary of the identified open issues in the RA and IM in HetNets and in hybrid HetNets – M2M networks. Some issues are related to the specific characteristics of LTE networks and the relevant eICIC methods, while others are specific to game-theoretical approaches.

2.3.7.1 LTE related challenges and open issues

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, particularly considering the impact of inaccurate and/or outdated information on the system performance.
2. Coordination of the frequency domain intercell interference for heterogeneous scenarios with both macrocells and small cells, since most of the works in the literature that have addressed the FFR concepts deal with macrocellular scenarios. Optimized solutions in the case of macrocells and small cells remain still as an open issue.
3. Joint optimization of ABS and CRE parameters in HetNets. While some works have addressed separately the two issues, or they have simply analyzed the impact of different settings, there are still few works that have addressed the joint optimization of both ratio of ABS frames and Cell Selection Bias.
4. 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 in way.

2.3.7.2 Open issues in the game-theoretical approaches

Most of the existing 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 can be identified:

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.
2. The need for studying and analyzing the existence, uniqueness, efficiency and stability of the equilibrium points of the resulting games.

3. 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.

2.3.7.3 Open issues in hybrid HetNet LTE – M2M networks

In M2M scenarios where traffic is served over a cellular infrastructure, multiple challenges are still open and need intensive research work. A summary of these challenges is given below.

1. The need for the implementation of low cost M2M devices supporting LTE standard: In order for LTE to be a successful platform for the support of M2M communications, the cost of LTE devices needs to be reduced. A 3GPP RAN1 group is currently working on this topic.
2. The need to manage very different QoS requirements, as the number and kind of M2M applications is open and not defined a priori: Some applications require hard constraints and disasters may occur if those are violated. Other applications have more relaxed constraints. Different from applications in classical cellular communications, based on human-to-human relations, where packet arrival periods can range from 10 ms to 40 ms, in MTC they can range from 10 ms to several minutes. Thus, how to successfully multiplex and schedule massive accesses with enormously different QoS characteristics turns out to be the most challenging task.
3. The need for appropriate resource allocation and scheduling algorithms: Packet scheduling constitutes the key Radio Resource management (RRM) mechanism to minimize the overall resource usage, while guaranteeing individual QoS service requirements. As a result, resource allocation and scheduling are expected to play a crucial role to deploy M2M communications through LTE. In general, scheduling is not part of the standardization work, but it is an implementation specific issue. However, signaling is standardized, thus any scheduling proposal should be in line with the set of control requirements. Leaning on this, several schemes have been devised for dynamically allocating resources with heterogeneous QoS requirements. However, with M2M scenarios 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. As a result, defining QoS classes is not an easy task. The literature is in general very limited in addressing the scheduling for M2M traffic in LTE systems. Schedulers designed for LTE cannot be applied for M2M, mainly due to the fact that H2H communications consider a limited amount of services which can be delivered through the network, and consequently a reduced set of QoS requirements for the different applications, compared to those that should be considered for M2M traffic.
4. The need for improvement in efficiency in radio resource utilization: H2H and MTC have to be handled in the framework of the same spectrum, for spectral efficiency requirements. In particular, time and frequency resources are to be shared between H2H users and MTC devices, thus resulting in co-channel interference among them. Such co-channel interference plays a detrimental role in degrading the performance of the LTE-A network with M2M communications. Furthermore, different types of users are characterized by different interference tolerance.
5. Analysis of impact of M2M utilization on LTE performances: Due to the differences in features between H2H and M2M traffic, there is the need to evaluate the impact that has to deal with these transmissions on the same LTE network. Typically, M2M applications receive or transmit only a small amount of data or require very low data rates, leading to an unreasonable ratio between payload and required information and non-optimized transmission protocols. Hence the impact of small packets transmitted periodically needs to be analyzed.

6. Management of Random Access Load: Related to the scheduling problem is also another important design consideration, which is how to design an efficient method for handling the random access (RA) load generated by a possibly huge population of M2M nodes attached to the network. Network congestion in random access channel (RACH) can lead to long delay and possible network access failure. To solve this problem, several solutions have been studied including time controlled access, staggered access, overload indicators to prevent MTC devices from access attempts, etc. In the RA process, the UE shall go through a preliminary stage, called Access Barring Check (ABC), where the UE should check whether the access to the network is prevented or not, based on the received System Information and its random-generation number. Once passed the ABC procedure, the UE starts transmitting a preamble to the eNB, which will be the actual load to the RACH. In 3GPP it is still on the table how to design the ABC mechanism, and some proposals can be found in literature.

3.Challenges to be addressed in WP1.3

In this section the selected activities (JRAs) in the framework of WP1.3 are presented. For each activity there is the description, the identification of the adherence and relevance with the identified fundamental open issues of section 2, a short presentation of the initial output/results, and a summary of the main achievements along with a roadmap for the future joint research work.

3.1 Task 1.3.1: Techniques for power-efficient communications

Task Leader: Jesus Gomez (CTTC)

This Task aims at developing techniques and algorithms for the optimization of energy efficient communications either from the terminals' or from a network's point of view. It is envisioned that the green wireless networks of the future will incorporate advanced communications techniques as well as energy harvesting devices enabling networks to be energy efficient, self-sufficient and sustainable. Within this task, new wireless channel models are developed that take into account the use of energy harvesting devises and the existence of removable energy sources. In addition, new advanced estimation and communication techniques are designed. Four JRAs have been formed in this task, based on the partners' interests:

- JRA on resource allocation and scheduling strategies for energy harvesting devices
- JRA on energy-efficient data collection and estimation in wireless sensor networks
- JRA on Joint Protocol Channel Decoding (JPCD)
- JRA on energy efficient probing in CSMA based multi-rate ad hoc networks

3.1.1 <u>JRA on resource allocation and scheduling strategies for energy harvesting devices</u>

Leader: Javier Rubio (UPC)
Main partners: Maria Gregori (CTTC), Miquel Payaró (CTTC), Antonio Pascual (UPC)

3.1.1.1 Description

Energy harvesting techniques try to provide longer connectivity to battery-powered nodes in wireless networks. In general terms, passive techniques collect energy from the environment (e.g. light, temperature, wind), whereas active techniques include wireless energy transfer from the transmitter. The main objective in this JRA is to develop resource allocation strategies for energy harvesting devices and to design techniques for recharging batteries by means of passive or active harvesting techniques and, thus, increase the lifetime of the network.

Traditional power allocation strategies (e.g., the well-known waterfilling) are no longer optimal when the transmitter has the ability to harvest energy. The traditional mean power constraint must be substituted by a set of energy causality constraints which impose that the energy used by the node must be smaller or equal from the energy harvested. Furthermore, specific scheduling must be performed in order to decide whether the base station will serve data or energy.

Because of these particularities, energy harvesting opens a new research paradigm in the design of optimal resource allocation strategies with specific considerations and challenges: (i) consider good statistical models for the energy harvesting process which permit the transmitter node to estimate and predict when energy is going to be harvested, (ii) apply realistic models for energy consumption, (iii) consider the hardware limitations and efficiencies, (iv) calculate the effect of inaccurate battery values information. Furthermore, also important is how to handle novel harvesting techniques in emerging systems and how to include them in MAC layer design.

3.1.1.2 Adherence and relevance with the identified fundamental open issue

This JRA has already covered and will continue to address some of the fundamentals open problems that have been presented in section 2.1.5.1. For example, it has partially addressed the resource allocation problem by considering battery-powered terminals as proposed in one of the open issues. Also, some models for the power consumption of decoders and how they relate with the data rate have already been studied, although more work is needed as stated in open issue 3.

Another research activity already initiated is the precise modeling for the energy packet arrivals based on Markov models and queuing theory as proposed in open issue 1. It includes scenarios that contain some intermediate nodes that act as relays, where the considered strategies take into account the overall energy minimization (by selecting the best route in terms of energy minimization). This is related with the proposed open issue 5.

Regarding the wireless energy transfer, one of the research approaches is on scheduling strategies for user grouping in order to improve the lifetime of the network (lifetime in terms of battery duration) as proposed in point 6 and 7 of the open issues. There are previous works that attempt to solve the problem of user grouping, but they focus on rate maximization. New energy-aware scheduling strategies need to be designed.

The following section presents the work that has already been published or submitted covering some of these fundamentals open issues.

3.1.1.3 Initial results

An energy harvesting transmitter operating in a point-to-point link through a discrete time fading channel was considered in [25]. Assuming non-causal knowledge of the harvested energy and channel state, the resource allocation that maximizes the mutual information was investigated by considering both the radiated power and the circuitry power consumption. A resource allocation strategy that asymptotically maximizes the mutual information along N independent channel accesses was derived. The *Boxed Water-Flowing* graphical interpretation was presented, which intuitively depicts the asymptotically optimal resource allocation.

A multi-user scenario where receivers are battery-power devices provided with energy harvesting sources was considered in [26] and [27]. The transmitter is provided with channel state information and battery status of the receivers. In particular, in [26] the problem is addressed from a theoretical point of view, where the resource allocation policy considers continuous assignment of power, bandwidth, and data rate. On the other hand, [27] considers finite constellation size with subcarrier allocation. Under this framework, suboptimal greedy policies were proposed, that minimize computational complexity of the overall algorithm. The results show that if the scheduler had information regarding the battery level of the users, the nodes improve their lifetime, and also enhance the average sum-rate of the system. The next two figures depict the time evolution of the average data-rate and the battery level of a multiuser system where the resource allocation strategy proposed in previous references has been applied.

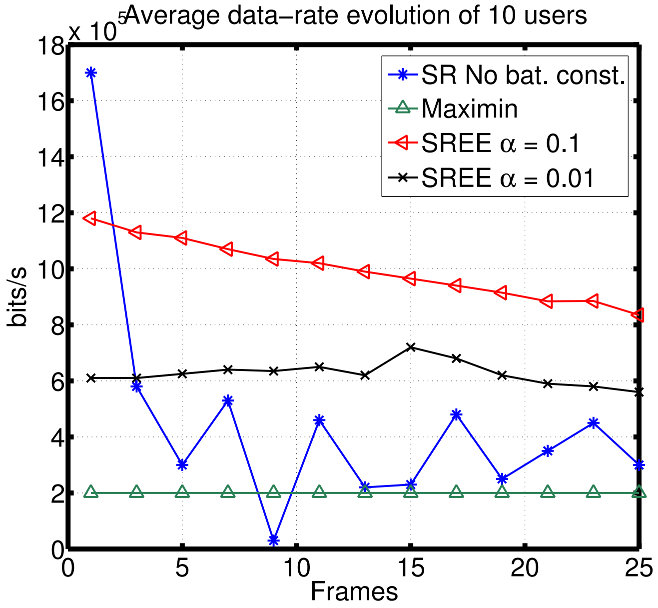

Figure 3-1: Evolution of the average data rate for different scenarios

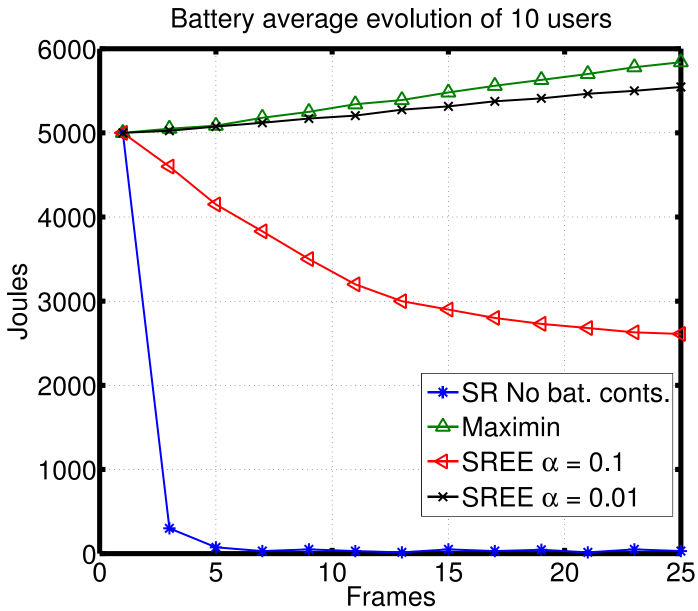

Figure 3-2: Evolution of the average battery level for different scenarios

The work presented in [28] extends the previous work in [26], now considering the multi-stream and multi-antenna case and incorporating the imperfection of the battery knowledge at the transmitter. Results show that battery knowledge imperfection presented a negligible loss with only 5 bits of quantization for feedback transmission. The next figure shows the average sum-rate obtained in the system with perfect battery knowledge and with a different number of bits used for battery quantization.

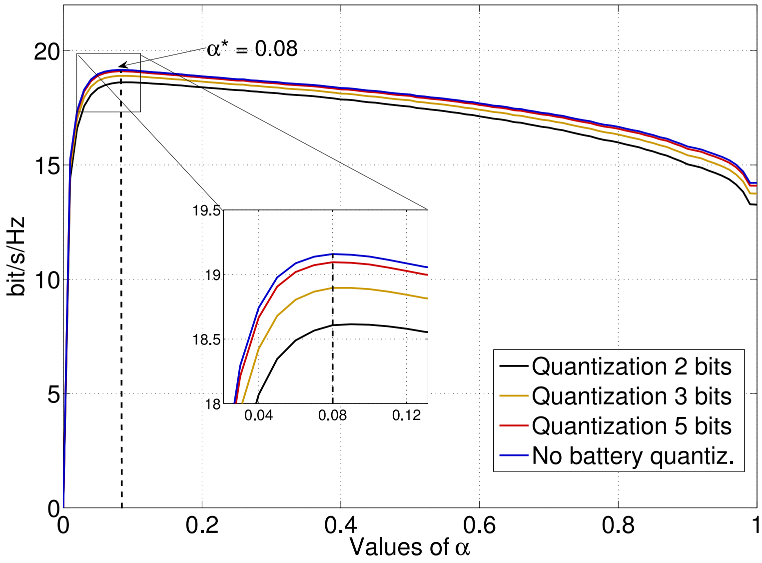

Figure 3-3: Mean achieved transmission rate as a function of alpha

Simultaneous wireless information and power transfer in a multi-user MIMO broadcast scenario was considered in [29]. The optimal covariance matrices under this scenario were derived and an iterative algorithm to compute them was proposed. The trade-off between the achievable sum-rate and the harvesting constraints yielding to the three-dimensional curve called *Rate-Energy region* is depicted in the figure below. More details of the scenario can be found in [29].

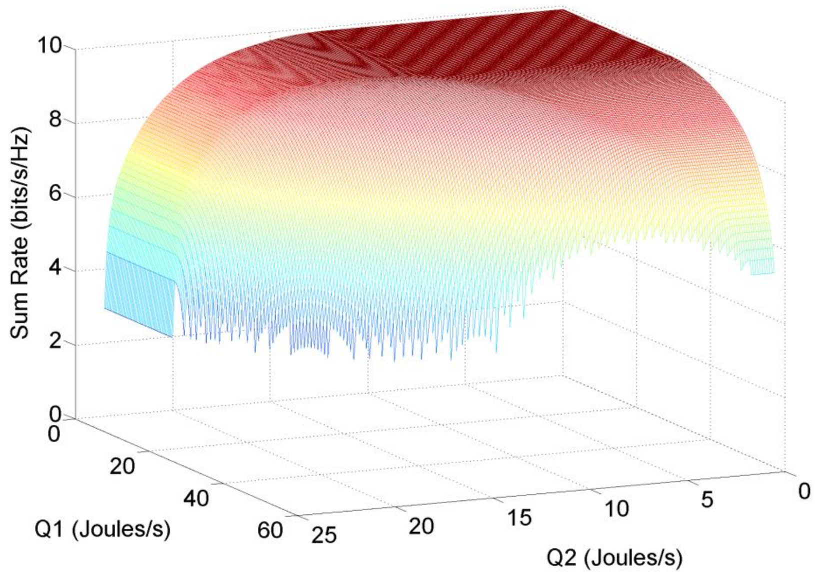

Figure 3-4: Representation of the 3-D Rate-Energy region

Possible future work, concerning resource allocation with battery-powered nodes provided with energy harvesting sources, includes:

- Modelling of the energy harvesting process to obtain tractable models to create low-complexity prediction schemes that can be used in wireless nodes.

- Designing and studying of possible resource allocation strategies in multi-user scenarios with special emphasis on cooperative communications among nodes to reduce transmission distances and, hence, reduce the network consumed energy. These strategies must take into account the different energy sinks at each of the network nodes.

Regarding simultaneous information and power transfer, there is still a lot of space for further research. One of the main ideas not considered in the previous work is the proper selection of users to be served by the transmitter at a given time. Since MIMO schemes are considered, the number of users is limited by the system's degrees of freedom. In that case, user selection algorithm for time scheduling must be considered, taking into account the two different types of users, information users and power transfer users.

3.1.1.4 Achievements and planned activities

Maria Gregori from CTTC and Javier Rubio from UPC jointly manage this JRA. There are also two more participants, Miquel Payaró from CTTC, who also contributes in Track 2, and Antonio Pascual Iserte from UPC. These partners developed the work presented in this deliverable.

The JRA is basically divided into two different sections: energy harvesting applied at the transmitter side and energy harvesting applied at the receiver side. Based on that, Maria Gregori and Miquel Payaró developed techniques for resource allocation in wireless networks where the transmitter is battery limited and has an energy harvesting source. They studied different scenarios, such us, the impact of the power consumption due to circuitry, or the optimal allocation considering any arbitrary input distribution at the receiver (finite constellation sizes), among others. Within this framework, they developed optimal (online and offline) techniques and also low-complexity sub optimal solution. They published several conference and journal papers. On the other hand, Javier Rubio and Antonio Pascual Iserte developed resource allocation techniques for wireless networks where the receivers are battery limited provided with energy harvesting sources. They studied the multi user scenario where the distance between the transmitter and the receivers is short (e.g., small cells) and incorporated the power consumption of the decoding process (at the receiver) in the proposed strategy. They also studied the scenario where the receivers are able to obtain energy from RF ambient signals and find the optimal resource allocation at the transmitter where the network is composed of receivers that want to receive information and energy simultaneously. Within this framework, they published several conferences and submitted one journal paper. The overall list of papers is a bit extensive and can be found in various relevant Newcom# reports.

Thanks to the level of activity, this JRA was selected to make a presentation of the current developments in the dissemination event in France Telecom in June 2013. The contents of the presentation were developed by the four integrands of the JRA and it was edited and presented by Miquel Payaró.

CTTC members had already started developing techniques for energy harvesting transmitters before the project. In fact, the journal paper entitled "Energy-efficient transmission for wireless energy harvesting nodes", and the conference paper entitled "Mutual information maximization for a wireless energy harvesting node considering the circuitry power consumption" had already been started before the project, but continued to be developed within the project. On the hand, the two conference papers entitled "Energy-efficient resource allocation techniques for battery management with energy harvesting nodes: a theoretical approach" and "Energy-efficient resource allocation techniques for battery management with energy harvesting nodes: a practical approach" were started just before the project, but they were developed and finished within the project.

The contribution of the technical material presented in the deliverable D13.1 was developed by the four participating members. Maria Gregori (CTTC) and Javier Rubio (UPC) performed the overall editing of the relevant section, both the state of the art and open issues, and the description of the work carried out (or to be performed).

There have been a couple of joint collaborations between Antonio and Miquel with Track 2. Two papers entitled “Hardware-efficient implementation of a femtocell/macrocell interference-mitigation technique for high-performance LTE-based systems” and “Interference management in LTE-based hetnets: a practical approach” have been presented and submitted, respectively. However, they were not in the context of JRA (harvesting techniques and power consumption models).

For the future, the plan is to have a direct collaboration with researchers in Track 2 within the context of this JRA. The idea is to be able to measure the power consumption of a real transceiver and incorporate such measurements in the algorithms that have already developed during the first year (and second year). The idea is to develop technical joint work and publish it during this second year of the project. Regular meetings for monitoring the work are planned for this purpose.

3.1.2 JRA energy-efficient data collection and estimation in wireless sensor networks

Leader: Francesca Bassi (CNRS/UPS)
Main partners: Michel Kieffer, Wenjie Li and Francesca Bassi (CNRS-UPS), Davide Dardari, Vincenzo Zambianchi and Gianni Pasolini (CNIT-UniBo), Sophie Fosson and Enrico Magli (CNIT-PoliTo), Javier Matamoros and Carles Anton-Haro (CTTC)

3.1.2.1 Description

This JRA leverages the different experiences and expertise of the partners, already active in this research domain, in order to provide innovative solutions for energy-efficient data dissemination and collection in sensor networks. The participants have defined a common research framework, described herein, and identified joint areas of interest and activities.

The goal of the JRA is twofold. First is the development of theoretical tools, still missing in the literature, for the assessment of the energetic performance of concurrent design strategies; this will enable to propose a set of design guidelines (i.e. which architecture/signal processing technique is better suited for a task under given energetic/complexity constraints), to orient the development of effective solutions. A second goal is to leverage the complementary expertise of the partners in order to propose practical design solutions, oriented to energy-efficient systems. The main focus will be on the development of new distributed solutions both for communication and signal processing in the network. Network-coded data dissemination and consensus algorithms are the respective techniques of choice. In both cases the effort will concentrate in the exploitation of the inherent redundancy in the physical data (temporal and spatial correlation of the measurements) in order to enhance performance. This will require joint optimization of the components of the network.

A sensor network can be mathematically described as a graph. The sensors are deployed according to a given topology and acquire some input signals, which have to be processed. In most scenarios, the final goal is to recover the acquired data or to extract some desired information from them. If a fusion center is available, typically the sensors just do some pre-processing or encoding on the acquired data, and then convey them to the fusion center that performs the main computations. In other cases, the operations are performed directly in-network, exploiting the possible cooperation among sensors.

Besides this general description, sensor networks may be mathematically modelled in very different ways. This is due to the fact that they build on many components such as sensors, communication links, and topology, as well as on the signals they have to acquire. Each component is then modelled according to the specific goal it is conceived for, which originates manifold possible setups. The main goal of this JRA is to develop distributed signal processing algorithms able to estimate the parameters of a spatial-temporal physical phenomenon in an efficient way in terms of energy consumption, complexity and radio resources usage. Different models will be considered.

3.1.2.2 Adherence and relevance with the identified fundamental open issues

One issue under investigation is the development of theoretical tools, still missing in the literature, for the assessment of the energetic performance of concurrent design strategies. Furthermore the JRA will propose practical design solutions oriented to energy-efficient systems. Another open issue that will be tackled by the JRA is the problem of robustness of the architecture towards local device failures or connectivity disruptions. In this respect, the main concern will be the assessment of the additional energetic cost that such events might cause.

3.1.2.3 Initial results

The first considered line of investigation concerns the choice of the data transmission technique to be implemented in the network. Solutions based on explicit routing of the information are not able to take advantage of the wireless nature of the shared medium, and result in inefficient energy use whenever the local measurements need to be disseminated in the network. A network-coding based dissemination strategy is considered in [52]. The sensors acquire local, spatially correlated measurements. The measurements need to be reconstructed within a given target distortion at multiple nodes acting as sinks. The goal is the minimization of the data exchanged among devices. The interest in this simple setup stems from the fact that it can be used as a fundamental block in network devoted to collaborative tasks (e.g. entity detection and tracking). Data dissemination is achieved using network coding: each node exchanges coded packets with neighbours. Each outcoming packet is the linear combination of the incoming packets, and of the local measurement. Each sink might attempt decoding after reception of a sufficient number of distinct coded packets. In standard network coding this number is equal to the total number of nodes. In [52] the spatial correlation among the measurements is exploited in order to enable reconstruction even for a much smaller number of received packets. This is obtained using Bayesian statistical models, which allow devising a decoding algorithm based on belief propagation. The whole process can be functionally described as a distributed source coding scheme, which underlines the fact that data dissemination and compression are achieved jointly. The communication rounds among neighbouring nodes need to comply with a special protocol (entailing partial decoding) in order to ensure high probability of convergence of the decoding algorithm. Simulation results on synthetic data confirm that this solution brings advantages with respect to standard network-coding dissemination of data, but at the cost of node complexity requirements fast increasing with the size of the network.

Another solution for restraining the cost of communication in the sensor network comes from optimization of the physical layer. In [53], [54] the following setup is considered: a number of sensors observe a set of correlated measurements. The goal is to reconstruct the spatial field at the sink. To do so, the agents are allowed to transmit simultaneously, since this reverts into lower transmission latency. Also in this case the correlation in the measurements is exploited to achieve compression. A beamforming scheme is employed, achieving an over-the-air compressed representation of the correlated set of spatial observations. The observations are then are encoded in a number of consecutive sensor-to-fusion center transmissions. This strategy minimizes the distortion in the reconstructed spatial field and, simultaneously, keeps the number of transmissions low (i.e. the compression ratio high).

The second main research topic in the JRA is represented by in-network distributed processing of the information. The interest in this topic arises from the possibility of working in absence of a special node (the fusion center), thus providing advantages in terms of robustness, failure tolerance, and communication cost. In [55] it is considered a setup where all the nodes observe the same physical phenomenon, represented as a sparse signal. The acquisition of the measurements is based on the compressed sensing principle. The goal of each node is the reconstruction of the common signal. As a consequence of the way the local observations are acquired, a sensor cannot perform satisfactory reconstruction exploiting its privy information. Exploitation of short-range communication among sensors enables the use of consensus techniques, resulting in the improvement of each local reconstruction. This class of distributed recovery algorithms is based on iterative thresholding methods and consensus techniques, which guarantee low complexity requirements.

One important issue is the comparison of the performance of distributed and centralized processing techniques. In [56] it is considered the problem of estimation of a scalar field over a bi-dimensional area. The network is supposed to have random topology. The goal is to provide the reconstruction of the spatial field at a fusion center. A mathematical framework is provided to assess the impact of distributed digital signal processing, achieved through a distributed compression technique based on signal re-sampling, with respect to the case where the processing is performed entirely by the supervisor. The trade-off between the energetic cost and the accuracy of the reconstruction in the considered scenario is also mathematically formalized. The theoretical analysis enables the conclusion that distributed digital signal processing techniques have relevant impact on the energetic performance of the sensor network.

In the first topic the partners are building a mathematical framework in order to provide attainable theoretical limits of the distortion-cost function related to communication. Moreover, attention is being paid at the joint optimization of the communication and reconstruction functions, leveraging the statistical properties inherent to the signal.

The second research topic concerns with distributed processing of the signal in the network. One scenario of interest is where a sparse signal is acquired via compressed sensing at the nodes, and needs to be reconstructed locally. Consensus techniques will be employed.

3.1.2.4 Achievements and planned activities

During the first year the activity in the JRA has been revolving around four main themes, briefly described in the following.

<u>Network-coded information diffusion in WSN</u>

Participants: Michel Kieffer, Wenjie Li, Francesca Bassi (CNRS-UPS)

The subject under investigation is the diffusion of locally acquired measurements to all the other nodes in the WSN, by means of network coding. The group at CNRS-UPS has been active on this topic prior to the beginning of the project: in particular, it had proposed a communication protocol leveraging the correlation among the measurements to reduce the communication cost: F. Bassi, C. Liu, L. Iwaza, M. Kieffer, Compressive linear network coding for efficient data collection in wireless sensor networks. In Signal Processing Conference (EUSIPCO), 2012 Proceedings of the 20th European (pp. 714-718).

In the context of the Newcom# project, this line of investigation has continued with the study of the theoretically achievable performance (in the information theoretic sense) of the protocol proposed in this paper. This activity has led to the submission of two papers

- W. Li, F. Bassi, M. Kieffer, Robust Bayesian compressed sensing over finite fields: asymptotic performance analysis, submitted to IEEE Trans. on Information Theory, December 2013: The problem of quantized measurements dissemination via network coding in a WSN can be recast as a Bayesian compressed sensing problem over finite fields. This paper derives necessary and sufficient conditions for almost sure recovery of the source, when the measurement vector is corrupted both by sensing and communication noise. This work provides several generalizations of known results, investigates for the first time the effects the sensing noise, and discloses the dependence of the performance on the sparsity of the sensing matrix.

- W. Li, F. Bassi, M. Kieffer, Noisy Bayesian compressed sensing over finite fields, submitted to IEEE Symposium on Information Theory, ISIT, January 2014: In the context of Bayesian compressed sensing on finite fields, this work derives necessary and sufficient conditions for almost sure recovery of the source, when the measurement vector is corrupted by communication noise. This work provides several generalizations of known results.

Consensus algorithms for joint learning and estimation

Participants: Michel Kieffer, Francesca Bassi (CNRS-UPS) and Davide Dardari, Vincenzo Zambianchi, Gianni Pasolini (CNIT-UniBo)

The subject under investigation is the joint diffusion and processing of information in the WSN. The considered problem can be summarized as follows: each sensor in the WSN measures the same physical state, possibly evolving in time, and the nodes will agree on a common estimate. An unknown parameter vector determines the sensing model and the distribution of the local sensing noises. Joint maximum likelihood estimation of the parameter and consensus-based distributed Kalman filtering are being considered. Their energetic performance is to be compared with alternative distributed strategies based on information diffusion and independent processing in each node. Work on this topic has begun within the Newcom# project. Preparatory work (planning and bibliographical documentation) has been performed by the partners during the first half of the year. The core of the activity has begun with the research visit (start November 2013) of V. Zambianchi (CNRS-UniBo) at CNRS-UPS. Two papers (one conference paper, one journal paper) are in preparation.

Distributed group testing in WSN

Participants: Michel Kieffer, Wenjie Li, Francesca Bassi (CNRS-UPS) and Davide Dardari, Vincenzo Zambianchi (CNIT-UniBo)

The considered problem is the self-detection of misbehaving sensors within the WSN. The task is to be accomplished using group testing. The protocol needs to work in a completely distributed fashion, in order to contain the communication cost of the self-maintenance operation. This topic has begun within the N# project. Preparatory work is ongoing, and includes the planning of a research visit of W. Li (CNRS-UPS) to CNIT-UniBo (beginning of Spring 2014, estimated duration of 6 months).

Distributed supported detection on jointly sparse signals

Participants: Sophie Fosson, Enrico Magli (CNIT-PoliTo) and Javier Matamoros, Carles Anton-Haro (CTTC)

Given different sparse signals with the same support, the aim is to develop distributed algorithms to recover the joint support. This may have relevant applications in networked technologies, e.g., for spectrum sensing in cognitive radio networks, where spectrum holes have to be detected with the final aim of optimizing the use of the available frequencies. In order to tackle this problem, distributed iterative methods have been proposed, based on iterative soft thresholding and consensus protocols. The most promising algorithm, called DiT, is presented in a joint paper:

- S. Fosson, J. Matamoros, C. Anton-Haro, E. Magli, Distributed supported detection on jointly sparse signals, accepted to IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP 2014.

The paper provided with a rigorous proof of its convergence and numerical simulations that illustrate its good performance. Comparisons with state-of-the-art greedy algorithms are proposed that show similar performance. The main advantage of DiT is that it does not require the prior knowledge of the sparsity level, which instead is necessary for greedy procedures. The core of this work has been developed during the visit of Sophie Fosson (CNIT-PoliTo) at CTTC (June 15 – July 15, 2013).

All partners participated in this deliverable. The joint work on the writing of the SoA section helped the partners to identify competences (e.g.: CNRS-UPS for network coding, CNIT-PoliTo for distributed compressed-sensing algorithms, CNIT-UniBo and CTTC for distributed field estimation). The editor of 2.1.2 was Francesca Bassi (CNRS-UPS), and the contributors: Francesca Bassi (CNRS-UPS), Davide Dardari (CNIT-UniBo), Sophie Fosson (CNIT-PoliTo), Javier Matamoros (CTTC). In section 3.1.2 the editor was Francesca Bassi (CNRS-UPS) and the contributors: Francesca Bassi, Michel Kieffer (CNRS-UPS) and Sophie Fosson (CNIT-PoliTo) and Javier Matamoros (CTTC) and Davide Dardari, Vincenzo Zambianchi (CNIT-UniBo).

A twin JRA in WP 2.2.2 is active, seeing the cooperation of CNIT-UniBo and CNRS-UPS. During the first year of the project the joint activity (within WP 1.3.1) about joint distributed learning and estimation in WSN has emerged as the candidate activity for the interaction with the JRA in WP 2.2.2. An action plan has been devised, starting with the identification of the Datasens platform in Bologna as the candidate testbed. F. Bassi (CNRS-UPS) visited the facility in July 2013. The experimental activity within WP 2.2.2 is expected to be carried on during the second year (Summer 2014).

Planned activity for the second year:

- Till May 2014: research visit of V. Zambianchi (CNIT-UniBo) to CNRS-UPS. Planned activity involves joint work on distributed learning and estimation in WSN. The work is ongoing, and a conference paper and a journal paper are the planned output. Addressed open issues: fully distributed design solutions, introduction of theoretical tools for the comparison of distributed and non-distributed systems.

- Spring 2014: planned research visit of W. Li (CNRS-UPS) to CNIT-UniBo. Estimated duration: 6 months. Planned activity involves work on distributed group testing. Addressed open issues: fully distributed design solutions, information theoretical characterization (achievable performance).

- Summer 2014: CNIT-UniBo and CNRS-UPS, beginning of the experimental activity in cooperation with Track 2.

3.1.3 JRA on Joint Protocol Channel Decoding (JPCD)

Leader: Michel Kieffer (CNRS)
Main partners: Pierre Duhamel, Michel Kieffer, Raymond Knopp and Nicolas Barbot (CNRS), Marco Chiani, Enrico Paolini and Mazzotti Mazzotti (CNIT-UniBo).

3.1.3.1 Description

This JRA aims to develop tools, based on joint protocol channel decoding [68], that exploit all information available at upper layers of the protocol stack to improve processing at lower layers, such as synchronization, channel estimation, channel decoding, and robust header recovery. The objective is to improve the energy efficiency of receivers by better synchronization capabilities, more efficient channel decoding, which reduces the need for packet retransmission.

The work will consider mainly four directions. First is the identification of specific parts of the communication chain where a joint processing, exploiting the redundancy in the protocol stack, may be helpful. Second, a specific formalism will be proposed in order to develop estimation techniques that can be used in as many different contexts as possible. Third, the already proposed techniques and newly developed ones will be applied in the context of LTE and LTE-A, and address any new issues raised by these communication systems. This part of the work will lead to collaborations with WP 2.3. Finally, the coexistence between JPDC and packet-level forward error correction techniques will be investigated, as well as how the design of such codes may exploit the redundancies present at several layers of the communication stack. Tools from signal processing, estimation and decision theory will be used to develop efficient JPCD techniques.

A first on-going research activity in the JRA is dedicated to the reliable classification of packet headers among various types. At many layers of various protocol stacks, a usually short field in the packet header is used to identify the type and thus the structure and the role of a packet. This type field is thus very sensitive to any transmission error. The goal is to develop reliable packet type classification techniques, to perform classification even in the presence of noise. For that purpose, estimators that take into account the global structure of a packet (including header check codes) and not only the type field are going to be used in order to take the most reliable decision on the packet type. This packet type classification is a first building block to address the open issue on JPCD of ROHC-encoded packets (Open issue 1 of section 2.1.5.3). ROHC packets are of several types, the reliable type classification technique allows one to identify this type and to adopt the best JPCD techniques for the content of the identified packet. This work will be considered jointly with CNIT/Bologna. This technique is also useful for the open issue related to medium reservation. Using robust packet type classification allows improving the amount of RTS/CTS/ACK packets received, and correctly identified. This improves the way the MAC layer is managed (Open issue 4). It may also have an impact on robust synchronization techniques (Open issue 5).

A second activity, related to Open Issue 2, is devoted to the construction of estimator for a priori probabilities of pilot bits. N. Barbot, the joint post-doc between CNRS and CNIT is currently considering for each bit a two-state Markov chain, which transition probabilities have to be estimated. The estimation has to be performed on a temporal window containing previously correctly received packets. A compromise between the size of the window, the adaptability of the estimator and the accuracy of the estimates has to be found. More sophisticated learning-based estimation techniques will be investigated with the help of CNIT during a stay of N. Barbot in Italy.

A third activity concerns the JPCD of packets which have been encrypted (Open issue 3). A single residual transmission error on an encrypted packet may waste its content once it is decrypted. This may be very helpful in the context of JPCD, provided that there is some redundancy/constraint in the encrypted message that may be used to check its validity.

A fourth activity is about the adaptation of HARQ mechanisms when JPCD is used (Open issue 7). More specifically, the focus will be on adaptation techniques of the redundancy increment in presence of JPCD techniques at the receiver. JPCD allows to better exploit the information available at the receiver in noise packets. The redundancy increase performed by HARQ may thus be tuned to be less aggressive.

The fifth activity is related to the adoption of packet-level coding in contexts in which reliability cannot be achieved by retransmissions (e.g., broadcasting, real-time applications). This activity will pursue two main objectives. The first objective is to investigate how redundancy and packet type classification may be exploited by a packet-level code in order to improve its performance. In packet-level coding, data units of some layer of the protocol stack (e.g., UDP packets at the transport layer) are used to fill a source block for the purpose of encoding. A similar block is then created on the receiver side for decoding. The a priori knowledge of some parts of the decoding block (i.e. the knowledge that some data in the block have higher reliability) may be exploited in order to achieve enhanced performance. Moreover, the code itself should be designed in order to exploit such a priori information. The second objective is to investigate the possibility to perform JSCD exchanging information between the application layer and the layer in which the packet-level code is implemented. In this case the packet-level code will not be a simple erasure code, but a code capable to cope with undetected packet errors, such as a verification-based decoder.

Finally, the partners also plan to study the impact on cross-layer optimization techniques at transmitter of the presence of JPCD techniques at receiver (Open issues 7, 9). Our aim is to collaborate with WP 2.3: Flexible communication terminals and networks, to implement the tools developed in this JRA in the context of OpenAir (Open issues 7, 9).

3.1.3.2 Adherence and relevance with the identified fundamental open issues

Several of the open problems introduced in the SoA section 2.1.5.3 have been identified and will be addressed in the way previously described. Summarizing, the work will be concentrated in the development of:

- Robust packet classification algorithms
- Pilot sumbol a priori probability estimation
- Robust recovery of encrypted packets
- Robust packet synchronization techniques
- A posteriori control techniques of the joint decoding efficiency

More practical developments will also be considered such as:

- Adaptation of the ROHC mechanisms to the JPCD scenario
- Evaluation of the behavior of MAC protocols when JPCD is activated
- Transposition of all developed techniques from Wi-Fi to LTE.

The participation to WP 2.3 will allow the partners to verify the proposed techniques in a more realistic context, especially for what concerns the practical developments.

3.1.3.3 Initial results

Earlier results by both participating institutions (CNRS and CNIT) in joint protocol-channel decoding include journal and conference papers on protocol-assisted channel decoding [73], reliable header recovery [83], [84], reliable burst segmentation [57], [59], [67], [80], modern iteratively decodable error correcting codes for the physical and the upper layers of the protocol stack, adaptive cross-layer optimization, and mechanisms to implement permeable protocol layers [89].

Protocol-assisted channel decoding techniques [73] use known bits in the packet headers as additional pilot bits that are employed by the channel decoder to improve its efficiency. These pilot bits are used to prune some path in the graph used for decoding in the case of convolutional codes. Gain of the order of 1 dB is observed at the channel level. When there is no interleaver before the channel decoder, the gain is mainly in terms of header-error rate. In presence of an interleaver, a gain is observed in bit error rate in decoded packets.

In reliable header recovery techniques [83], [84], known header bits, as well as header check sequences are combined to improve the header decoding efficiency. The trellis of the CRC or checksum of the packet is considered. Known bits in the header serve as pilot bits. An a posteriori estimate of the unknown bits is then performed. Due to the complexity of the trellis associated to CRCs or checksums, suboptimal decoding techniques have been proposed. They split the code in several parts, assumed independent. As many smaller trellises are then obtained to get a manageable decoding complexity.

Several reliable burst segmentation techniques have been proposed [57], [59], [67], [80]. Usually, the presence of a synchronization word is assumed, as in [67], [80]. Several hypothesis testing techniques have been proposed to perform variable-length frame synchronization. In absence of synchronization word, assuming a length field is present in the header of the variable-length frame, the conventional Hard Decision (HD)-based frame synchronization can be performed when the noise is moderate. In [100], the HEC field has been employed to perform frame synchronization of variable-length IP frames using a three-state automaton adapted from [101]. In several situations, e.g., when the HEC field is erroneous itself or when its length is too short compared to the header size, false alarms can hamper the efficiency of the algorithm. In [57], [59] several improved frame synchronization algorithms are proposed. They exploit soft information at the output of the channel (or channel decoder) as well as redundancy in the protocol layers (synchronization word, known fields, Cyclic Redundancy Check (CRC) or checksums, etc). Frame synchronization is formulated as a maximum a posteriori (MAP) estimation problem. Trellis-based hold-and-sync techniques for frame synchronization are described first. A modified BCJR algorithm is used to estimate the locations of frame boundaries. Then, an adaptation of the reduced-complexity Sliding Window [102] variant of the BCJR algorithm is proposed to get a low-delay and reduced-complexity version of the previous algorithm. Second, an improved version of an on-the-fly 3S FS automaton [100] is also presented. It combines robust header recovery techniques from [83] with Bayesian hypothesis testing inspired from [67], [80] to localize frame boundaries via a sample-by-sample search. The techniques presented are quite general. They are illustrated with the FS of WiMAX MAC frames aggregated in bursts transmitted to the PHY layer, but are easily extended to other protocols where frame aggregation is performed.

Mechanisms to implement permeable protocol layers are described in [89]. Techniques to exchange efficiently soft information between protocol layers are described. These techniques, implemented within receivers are transparent to equipments without joint decoding abilities.

CNRS/EURECOM has developed the OpenAir interface on which the JPCD techniques plan to be tested.

3.1.3.4 Achievements and planned activitiess

This JRA involves the CNRS (P. Duhamel, M. Kieffer, R. Knopp, N. Barbot), and CNIT Bologna (M. Chiani, E. Paolini, M. Mazzotti). The joint work with CNIT started at the end of the first year of N#. During the first year of NEWCOM#, the several open issues related to JPCD have been identified and quite a lot of time was devoted to the identification of joint research activities. CNRS has hired several first-year master students. They have obtained the first results in the reliable packet classification techniques, which have been published in:

- Kai Wan, Jinghui Liu, Michel Kieffer, Pierre Duhamel, Reliable packet type estimation via joint protocol-channel decoding, Proc. ICASSP 2014, to appear: This paper presents reliable packet type classification techniques. The global structure of a packet (including header check codes) and not only the type field is taken into account to take the most reliable decision on the packet type.

In spring 2014, a second-year master student will be hired by CNRS to finish the work on packet classification, apply this technique in various scenario, in particular to evaluate the performance of MAC protocols when JPCD is used. Students will also address the problem of JPCD of encrypted packets. A visit of one or two students is planned to CNIT.

In January 2014, CNRS and CNIT have hired a post-doctoral fellow (N. Barbot) to investigate the OpenAirInterface and to identify more clearly the way JPCD techniques may be implemented in this simulator. He will have to adapt already developed basic JPCD building blocks. Several exchanges between CNRS/UPS and CNRS/EURECOM will be needed for that purpose. This work will be done within WP 2.3. N. Barbot is currently working on pilot bit a priori probability estimation. More sophisticated estimators for the structure of packets will be investigated with CNIT.

In spring 2014, CNRS will apply for a French-Italian PhD grant to collaborate more efficiently with CNIT on the topics already identified by the second-year master students and by the Post-doc. In his PhD, the student, which may be one of the second-year master student will have to develop new JPCD adapted for LTE and beyond and evaluate the impact of these techniques in OpenAirInterface.

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

Leader: Mehmet Koseoglu (Bilkent)
Main partners: Mehmet Koseoglu and Oya Ekin Karasan (BILKENT), Lin Chen (CNRS/UPSUD)

3.1.4.1 Description

In this study, the tradeoff between the energy consumption and throughput in CSMA based ad hoc networks will be exploited by adaptively controlling the channel probing rate and the modulation/coding profile. So far, the energy consumption minimization in the MAC layer by adjusting the probing rate for a fixed modulation/coding scheme has been investigated and the optimum probing rate and the corresponding optimum throughput which minimizes the energy consumption in the network under ideal channel conditions has been obtained.

In the next stage of the JRA, the partners will follow a cross-layer approach which will jointly take the fading channel conditions and perceived MAC contention levels into account in order to set the probing rate and modulation/coding scheme adaptively. In the physical layer, channel adaptation methods reduce transmission errors by adapting to the channel conditions. In addition to improving throughput by reducing bit errors, channel adaptation has also implications from the perspective of the MAC layer. Adapting the transmission bit rate affects the frame lengths and packet error rates, which in turn impact the MAC layer performance. For example, using a higher level modulation/coding profile decreases the frame transmission duration which subsequently results in less contention for the MAC layer. On the other hand, the frame error rate increases while using higher level modulation/coding profile. Hence, there is a trade-off between the performances of the physical and MAC layers. In this study, the partners will jointly investigate physical layer transmission rate adaptation along with the probing rate adaptation in the MAC layer to minimize the energy consumption per transmitted bit.

3.1.4.2 Adherence and relevance with the identified fundamental open issues

In this JRA, the goal is to address some of the open issues presented in Section 2.1.5.4. As mentioned in the SoA section (open issue 1), one of the main concerns 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. So, developing an energy consumption model and a distributed energy efficient MAC method is important from the perspective of many CSMA-based wireless networking protocols. However, in the literature most of the energy efficiency studies are confined to a specific standard and a general model of energy efficiency is lacking as mentioned in the SoA section (open issue 3).

Recently, there is a growing interest on developing carrier-sensing rate adaptation algorithms to achieve throughput-optimality in a CSMA network. In these algorithms, each node senses the channel at a rate which increases with its packet queue length (or virtual queue length). As packet queues grow, the nodes may sense the channel at arbitrarily high rates. However, the increased energy consumption due to such increased carrier-sensing rate has not been investigated to the best of our knowledge as mentioned in the SoA section (open issue 4). This JRA will address the energy consumption issues regarding distributed CSMA protocols. Most of the studies in the literature do not take physical layer performance into account in their analyses and we will address these issues jointly with MAC layer.

In addition to the analysis of energy consumption for ad hoc CSMA based networks, design of distributed energy-efficient MAC schemes remains a challenging open problem due to imprecise channel conditions and due to dependence on the decisions of other nodes in the network as mentioned in the SoA section (open issue 6). This JRA plans to design distributed methods which minimize the total energy consumption in the network.

3.1.4.3 Initial results

So far, the partners have studied the following question: What is the optimum channel probing rate which maximizes the number of transmitted bits for the lifetime of the node which is limited by its energy budget. If the probing rate is selected too small, the nodes will rarely transmit a packet and spend most of their lifetimes in the sleep mode. In this case, a node consumes its energy budget mostly in the sleeping state albeit sleeping has minor energy consumption. A very low probing rate can improve the duration of service but it will not improve the number of bits that it can transmit during its lifetime.

If the probing rate is selected too large, the nodes will frequently wake-up and sense the channel to transmit a packet. Although it is usually omitted in the literature, each time a node senses the channel and finds it busy; a small amount of energy is spent without making a transmission. So, a very high probing rate will also result in energy inefficiency.

The partners performed simulations and proposed an energy consumption model for both single-hop and multi-hop CSMA networks. The simulation results for the single-hop case are plotted in Figure 3-5 along with the results from the model for different number of nodes, *N*. In the figure, the two major components of total energy consumption, energy consumed for sleeping and energy consumed for sensing are plotted. Total energy consumption presents a trade-off between these two major components. The figure also shows that the proposed model for the single-hop network predicts the energy consumption accurately as a function of throughput. Another observation that can be made from the figure is that the energy consumption increases with *N*.

Energy consumption of the multi-hop network with the same parameters as the single-hop case can be seen in Figure 3-6. The average energy consumption of the network per transmitted bit and the components of the energy consumption are also shown for *d*=2, 3 and 10 along with the values obtained from the proposed analytical model. At low throughputs, sleeping increases the energy consumption per transmitted bit, and at high throughputs, the energy spent for carrier sensing dominates. As *d* increases, the energy spent for carrier sensing becomes significant because the probability that a carrier sensing attempt fails increases due to higher interference.

These initial results show that the energy consumption is minimized at lower throughput than the maximum throughput achievable. Future work will include physical layer adaptation parameters to achieve minimization of energy consumption jointly over both physical and MAC layer. The main motivation in this study is to analytically obtain this energy-optimum throughput value as a function of various network parameters such as number of nodes and channel fading conditions and to design an adaptive multiple access method which can achieve this optimum throughput in a distributed fashion.

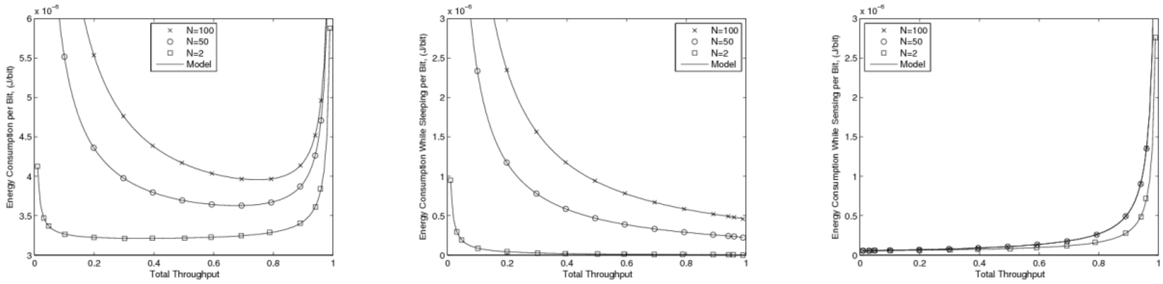

Figure 3-5: Left: The total energy consumption of a single-hop CSMA network - Middle: Energy consumption due to sleeping - Right: Energy consumption due to carrier-sensing

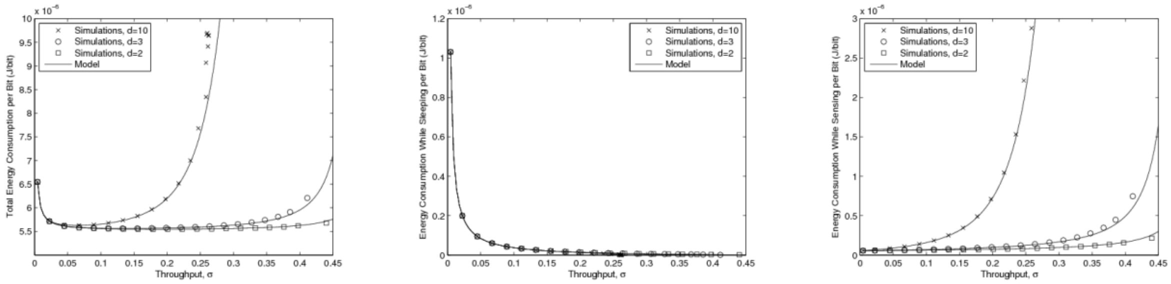

Figure 3-6: Left: The total energy consumption of a multi-hop CSMA network - Middle: Energy consumption due to sleeping - Right: Energy consumption due to carrier-sensing

The collaborating partners have already developed a mathematical model for energy-efficiency by considering the MAC layer only for a single hop CSMA network using an ideal channel assumption and extended the model to multi-hop CSMA networks using the same ideal channel assumptions.

3.1.4.4 Achievements and planned activities

In the first year of the N#, M. Koseoglu and E. Karasan (BILKENT) investigated the energy efficiency of a CSMA-based wireless network from a MAC-layer perspective. This research established the foundations of the joint research direction with Lin Chen (CNRS/UPSUD) in which partners investigate the energy efficiency from a joint PHY-MAC layer view. In this joint research activity, the partners have now prepared a draft on this topic. Besides this activity, M. Koseoglu and E. Karasan investigated the effect of spatial distribution of nodes on throughput modeling of a CSMA network. These studies led to the following publications and dissemination activities.

- M. Koseoglu and E. Karasan, “Energy-optimum Throughput and Carrier Sensing Rate in CSMA-based Wireless Networks,” IEEE Transactions on Mobile Computing, accepted for publication: The paper proposed an energy consumption model for a CSMA-based wireless network. The authors showed that there is an optimum value of throughput at which the CSMA network has to be operated to minimize energy consumption. This energy-optimum throughput is shown to be substantially lower than the maximum throughput and the gap increases as the degree of the conflict graph increases for multi-hop networks. The last stages of the work reported in this paper are developed within the Newcom# project.

- M. Koseoglu and E. Karasan, “Spatio-Temporal Analysis of Throughput for Single-Hop CSMA Networks,” IEEE Communications Letters, accepted for publication: The paper investigated throughput of a CSMA network where the nodes are randomly distributed over an area. Previous studies neglected the effect of the spatial distribution of nodes in throughput analysis of CSMA networks. By considering this effect, the proposed throughput analysis improved the state-of-the-art model significantly. All of the work reported in this paper is developed within in the N# project.

- Presentation by M. Koseoglu and E. Karasan, "Energy-optimum Throughput and Carrier Sensing Rate in CSMA-based Wireless Networks", in the Industry Workshop organized by Aselsan Inc. (http://www.aselsan.com/) on Nov. 2013 related to the work proposed in the first paper.

The collaborating partners have prepared a draft on energy efficient adaptive modulation and coding for CSMA networks. M. Koseoglu participated in Newcom# Dissemination Event held in Lisbon, 21-23 Jan. 2014 and made a presentation about this joint research activity entitled

"Cross-layer Performance Optimization of Adaptive Modulation and Coding for CSMA Networks" authored by M.Koseoglu, E.Karasan and L.Chen. The contribution to the deliverable is written by M. Koseoglu and E. Karasan after a discussion of future research direction with L. Chen.

The work accomplished so far addresses most of the open issues that we have stated in the deliverable which can be broadly defined as the cross-layer energy efficiency analysis of wireless CSMA-based networks. This is an improvement over most of the previous energy efficiency studies which either focus on the MAC layer or the physical layer in isolation. We consider both layers jointly to achieve more efficient communications. The following action plan for the second year extends our techniques to include more general scenarios:

- Extend the study beyond the AWGN channel. Particular channels such as channel properties of the terrestrial radio networks and underwater acoustic networks is planned to be incorporated.

- Remove the ideal CSMA model assumption to incorporate frame losses due to the MAC layer.

- Investigate the effectiveness of transmission power control mechanism on the energy efficiency of CSMA network.

- Develop a simulator for the considered scenarios to investigate the accuracy of the model. The developed simulator will be customizable for different channels and different multiple access algorithms.

- Investigate collaboration options with the Track 2. We plan to investigate possibility of implementation of the proposed methods at the FLEXTOP facilities.

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

Task Leader: Adrian Kliks (PUT)

The Task is devoted to the investigation and development of various PHY layer techniques for interference handling and mitigation. The main research areas are: (i) adaptive spectrum shaping techniques such as beamforming for low-interference communication, (ii) issues related to the reduction of out-of-band radiation, enhanced filtering, advanced MIMO techniques and adaptive signal processing, all directed by higher layers for interference avoidance and management, (iii) analysis of the effects of nonlinear elements in the transceiver chain (like power amplifiers or digital-to-analogue converters) in the presence of adjacent-channel interference constraints, and (iv) interference avoidance techniques devoted for Filter-Bank based MultiCarrier (FBMC) and Generalized MultiCarrier (GMC) systems. Based on the experience of partners involved in this task, two consolidated JRAs have been identified, projecting various investigation interests:

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

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

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

Leader: Adrian Kliks (PUT)
Main partners: Carla Oliveira, Michał Maćkowiak and Luis Correia (INOV), Màrius Caus and Ana I. Pérez Neira (UPC), Hanna Bogucka, Adrian Kliks and Paweł Kryszkiewicz (PUT)

3.2.1.1 Description

The goal of this JRA is to investigate various advanced MIMO techniques for the filter-bank multicarrier transmission and for WBAN systems. In the following sections the description of the ongoing work, as well as the plans and expected outcome are presented.

Current wireless communication systems rely on multicarrier modulations (MCM) to combat the multipath fading of wireless channels. The general trend consists in implementing the orthogonal frequency division multiplexing (OFDM) technique. The beauty of OFDM stems from the fact that the global communication system can be modeled like a set of parallel flat fading channels. However this is achieved by transmitting redundancy in the form of a cyclic prefix (CP). In addition, the subcarrier signals that are transmitted on each subchannel are shaped with the rectangular pulse, which has a sync-like shape. Hence, the power spectral density of subcarrier signals exhibit large side lobes. To overcome some of the OFDM limitations, more advanced techniques can be used to partition the band [109]. In this task, the focus is on the study of the filter bank multicarrier modulation based on the transmission of OQAM, which is known as (FBMC/OQAM) or (OFDM/OQAM) [150]. The FBMC/OQAM technique does not transmit redundancy and, therefore, the spectral efficiency is increased with respect to OFDM. Moreover, the analysis and synthesis filter bank stages benefit from pulse shaping techniques. This makes FBMC/OQAM the ideal choice in cognitive radio and multiple access networks, where nodes are unlikely to be tightly synchronized.

It is well-known that one of the drawbacks of FBMC/OQAM has to do with the fact the orthogonality between subcarriers is satisfied in the real domain and, thus, the channel may destroy this property yielding inter-carrier and inter-symbol interference. To remove the interference that leaks from surrounding positions in the time-frequency grid, the channel has to be perfectly equalized before the real part is extracted. If the frequency selectivity of the channel becomes severe, the single-tap equalization performs poorly and multi-tap equalization is mandatory [152]. Provided that channel state information (CSI) is available at the transmit side, the performance can be improved by performing linear precoding because the noise is not enhanced. In [153] it is shown how FBMC/OQAM can benefit from linear precoding. In view of this, the emphasis of this task is on the study of the impact of linear precoding on the average transmitted power. So far this issue has only been addressed in [154]. Following a similar approach, the objective of this task is to evaluate the average power at the output of the modulator when subband signals are processed by multi-tap precoders. The expressions provided in [154] are only valid for the technique presented therein. The aim here is to present more general results.

The algorithms developed for classic MIMO systems could be adopted by the virtual MIMO scenarios, as for example for wireless BAN systems. Virtual MIMO consists of clusters of antennas, on the transmitter (Tx) and receiver (Rx) sides, to behave like a multi-antenna system. A condition to get MIMO channel capacity gains is the decorrelation between the various MIMO links (i.e., pairs of Tx and Rx antennas), the independence of these links being related to the propagation conditions in the radio channel. In general, the difference in the Signal to Noise Ratio (SNR) between signals should be low (e.g., below 10 dB), as well as the correlation (e.g., below 0.7), in order to provide the desired capacity gains [156].

This JRA considers that the modelling of wearable antennas in BANs is separated into antennas in the vicinity of the body, including the body dynamics, and a street environment. The coupling between antenna and the body is addressed using a statistical description of the wearable antenna patterns (e.g., average on-body antenna gain) at different locations on the body [157]. The user's mobility is considered, based on a motion capture analysis [158]. A realistic multipath scenario is taken into account, consisting of clusters of scatterers, and a Geometrically Base Statistical Channel (GBSC) model adapted to BANs is used to calculate the multi-path components (MPCs).

3.2.1.2 Adherence and relevance with the identified fundamental open issues

There are two main open issues under consideration, which will be investigated in more detail:

- To efficiently combat the channel frequency selectivity in the context of FBMC/OQAM, the symbols can be precoded on a per-subcarrier basis. If the linear precoder performs a multi-tap filtering, the power may be boosted as if no precoder was used. To characterize this effect, this task is focused on the transmitter chain with the object of analyzing the output of the modulator. This matches with one of the open challenges described in Section 2.2.3.1.
- Investigation of advanced MIMO techniques (i.e., virtual MIMO) applied to Body Area Networks and LTE will be explored in order to reduce the required SNR (i.e., lower emission) and preserve the required bitrate, under an energy efficiency perspective.

3.2.1.3 Initial results

System model and problem statement addressing the first open issue

The transmitted signal at the synthesis filter bank output is given by [151]:

$$s[n]=\sum_{m=0}^{M-1}\sum_{k\in Z}\left(b_m[k]*d_m[k]\theta_m[k]\right)f_m\left[n-k\frac{M}{2}\right] \tag{3.2.1.1}$$

with

$$f_m[n]=p[n]\exp\left(j\frac{2\pi}{M}m\left(n-\frac{L-1}{2}\right)\right). \tag{3.2.1.2}$$

Note that (3.2.1.1) indicates that the band is split into M subbands identified with the index m. The bank of filters that are used to generate the synthesis filter bank is given by $\{f_m[n]\}$. As (3.2.1.2) shows, the transmit pulses are uniformly spaced, thus they are generated by shifting the low-pass prototype pulse $p[n]$, the length of which is L. The low-rate signal conveyed on the m-th subband are obtained by convolving the OQAM symbols $d_m[k]\theta_m[k]$ with the linear precoder $b_m[k]$. Hence, symbols are precoded on a per-subcarrier basis. In general, $b_m[k]$ is different from zero for $-L_b \le k \le L_b$. In this sense, in [152], [153] it is demonstrated that $L_b = 1$ offers the best trade-off between complexity and robustness. Based on that we stick to the 3-tap case and, therefore, $-1 \le k \le 1$. As for the OQAM symbols, the term $d_m[k]$ denotes the real-valued symbol drawn from the PAM constellation transmitted in the mth subband and kth time instant. The phase term is selected as

$$\theta_m[k]=\begin{Bmatrix} 1 & k+n\ even \\ j & k+n\ odd \end{Bmatrix} \tag{3.2.1.3}$$

to ensure that adjacent symbols along the time-frequency grid have a difference of phase equal to $\pi/2$.

Considering that a frame transmission contains N multicarrier symbols, the average power per-frame can be computed as follows

$$P_T = \sum_{n=0}^{L_N-1} E\left\{|s[n]|^2\right\} = \sum_{n=0}^{L_N-1}\sum_{k,s=0}^{N-1}\sum_{m,l=0}^{M-1} E\{(b_m[k]*d_m[k]\theta_m[k])(b_l[s]*d_l[s]\theta_l[s])\} \quad (3.2.1.4)$$
$$x f_m\left[n-k\frac{M}{2}\right] f_l^*\left[n-s\frac{M}{2}\right]$$

where $L_N = (N-1)M/2 + L$ accounts for the total number of samples. The expectation is taken over precoders and symbols. Transmit filters are treated as random variables because they depend on the channel. It must be mentioned that it is assumed that channel is constant within a frame, so precoders are constant as well but they may vary in the next frame. As for the symbols, assuming that $E\{d_m[k]d_l[s]\} = \delta_{m,l}\delta_{k,s}$, then (3.2.1.4) becomes

$$P_T = \sum_{n=0}^{L_N-1}\sum_{k,s=0}^{N-1}\sum_{m=0}^{M-1} E\{(b_m[k]*d_m[k]\theta_m[k])(b_m[s]*d_m[s]\theta_m[s])\} \quad (3.2.1.5)$$
$$x f_m\left[n-k\frac{M}{2}\right] f_m^*\left[n-s\frac{M}{2}\right]$$

with

$$E\{(b_m[k]*d_m[k]\theta_m[k])(b_m[s]*d_m[s]\theta_m[s])\} =$$
$$\sum_{z,t=0}^{N-1} E\{d_m[t]\theta_m[t]d_m[z]\theta_m^*[z]b_m[k-t]b_m^*[s-t]\} = \sum_{t=0}^{N-1} E\{b_m[k-t]b_m^*[s-t]\}. \quad (3.2.1.6)$$

Without loss of generality precoders can be expressed as:
$b_m[k] = \sqrt{p_m}\,u_m[k]\left(|u_m[-1]|^2 + |u_m[0]|^2 + |u_m[1]|^2\right)^{-0.5}$,

where p_m is the power allocated to band m. Then, it is easy to verify that in the single-tap case (3.2.1.5) is recasted as:

$$P_T = \sum_{k=0}^{N-1}\sum_{m=0}^{M-1} p_m\ , \quad (3.2.1.7)$$

bearing in mind that the pulses are properly scaled, that is $\sum_{n=0}^{L-1} |f_m[n]|^2 = 1$. To determine whether the transmit processing based on multi-tap filtering boosts the power, we should compare (3.2.1.5) with (3.2.1.7). Unfortunately, it is not a trivial task to derive closed-form expressions when the processing carried out at transmission is wideband.

Ongoing work and challenges

By starting we focus on the precoders that are designed according to the frequency sampling approach [153]. This means that the taps are designed by solving this system of linear equations on the even subbands.

$$\begin{bmatrix} \exp(-j(-\pi/2)(-1)) & \exp(-j(-\pi/2)0) & \exp(-j(-\pi/2)1) \\ \exp(-j(0)(-1)) & \exp(-j(0)0) & \exp(-j(0)1) \\ \exp(-j(\pi/2)(-1)) & \exp(-j(\pi/2)0) & \exp(-j(\pi/2)1) \end{bmatrix} \begin{bmatrix} u_m[-1] \\ u_m[0] \\ u_m[1] \end{bmatrix} = \begin{bmatrix} 1/H(w_m^{-1}) \\ 1/H(w_m^{0}) \\ 1/H(w_m^{1}) \end{bmatrix} \quad (3.2.1.8)$$

On the odd subbands the problem reads as follows

$$\begin{bmatrix} \exp(-j(\pi/2)(-1)) & \exp(-j(\pi/2)0) & \exp(-j(\pi/2)1) \\ \exp(-j(\pi)(-1)) & \exp(-j(\pi)0) & \exp(-j(\pi)1) \\ \exp(-j(3\pi/2)(-1)) & \exp(-j(3\pi/2)0) & \exp(-j(3\pi/2)1) \end{bmatrix} \begin{bmatrix} u_m[-1] \\ u_m[0] \\ u_m[1] \end{bmatrix} = \begin{bmatrix} 1/H(w_m^{-1}) \\ 1/H(w_m^{0}) \\ 1/H(w_m^{1}) \end{bmatrix} \quad (3.2.1.9)$$

In notation terms, let $H(w)$ be the channel frequency response. The target points are given by $w_m^{-1} = 2\pi m/M - \pi/M$, $w_m^0 = 2\pi m/M$ and $w_m^{-1} = 2\pi m/M + \pi$. Since the coefficients $\{u_m[k]\}$ depend on the channel frequency response, solving (3.2.1.6) implies computing the expectation of the ratio of two random variables. To this end, we will study if the approximation derived in [155] may pave the way to characterize (3.2.1.6). Note that formulating (3.2.1.6) in a closed-form expression is definitely challenging and it depends on the design criterion that has been followed to set the value of the taps.

Numerical results

To show the importance of performing multi-tap precoding Figure 3-7 depicts the BER against the delay spread when the power delay profile decays exponentially and the energy bit to noise ratio is 20 dB. Different precoder lengths and subcarrier spacing have been simulated. Since the bandwidth is set to 10MHz, the subcarrier spacing is 9.76 KHz for M=1024. When M=512 or 256 the subcarrier spacing is 19.53 or 39.06 KHz. As the delay spread increases the channel frequency selectivity becomes stronger and, therefore, the channel variations in the subcarrier pass band region may not be perfectly compensated. The problem is even more challenging when the subcarrier spacing is widened. This implies that the orthogonality may be destroyed and then, the symbols transmitted in the neighborhood around the position of interest will cause interference. For this reason the BER deteriorates as the delay spread and the subcarrier spacing increases. However, the 3-tap filtering offers an increased resilience against multipath fading when compared to the single-tap case. This justifies the utilization of broadband precoders.

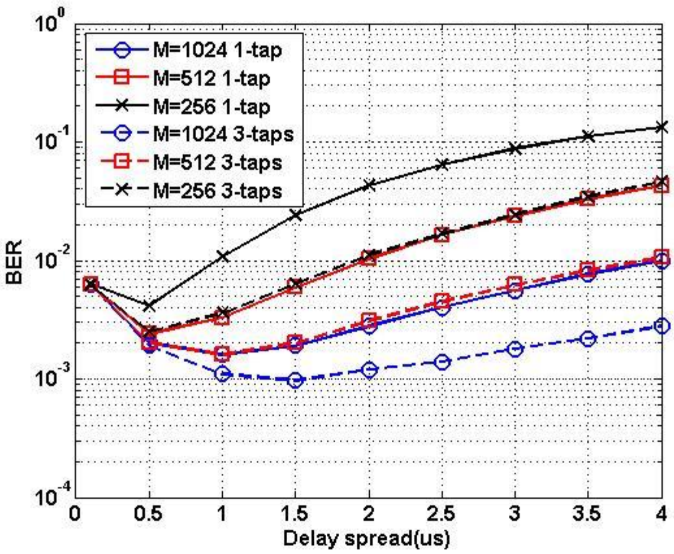

Figure 3-7: BER against the delay spread for energy bit to noise ratio equal to 20dB

MIMO techniques (i.e., virtual MIMO) applied to Body Area Networks

Some initial simulations have been performed using the GBSC simulator, in order to define a common data format among the JRA's partners. The preliminary scenario considers a user running in a street environment, wearing several on-body sensors, and transmitting information to a base station (with 2 antennas), located on the left side in the middle of the run path, Figure 3-8.

The following nine on-body antenna placements are analysed:

- TO_F and TO_B (front and back side of the chest),
- WA_F (front side of the waist),
- HE_F, HE_B, HE_L and HE_R (front, back, left and right side of the head),
- AB_L and AB_R (left and right side of the arm).

The output data format from the GBSC simulator is the received power at the base station antennas, *rx_power* (*inaid, outaid, frameid, freqid, simid*), where:

- inaid: id of on-body antenna,
- outaid: id of base station antenna,
- frameid: time frame number,
- freqid: id of frequency (definition of frequencies is provided in the array),
- simid: simulation number.

For the initial study, two frequencies, separated by 20 MHz (e.g., LTE bandwidth), were selected:

- 2620 MHz
- 2640 MHz

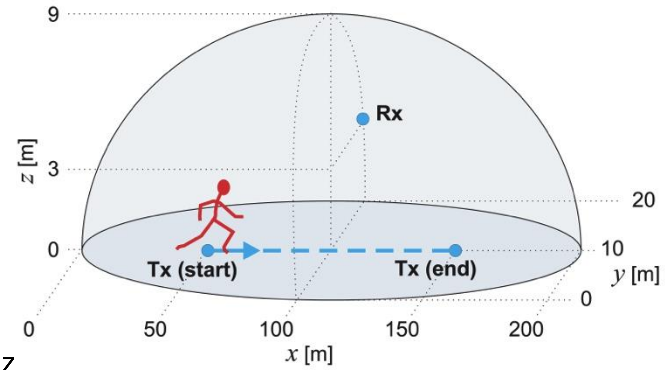

Figure 3-8: Simulation Scenario

Figure 3-9 presents an example of the received power at the base station, for the analysed frequency bands, when the AB_L antenna is transmitting.

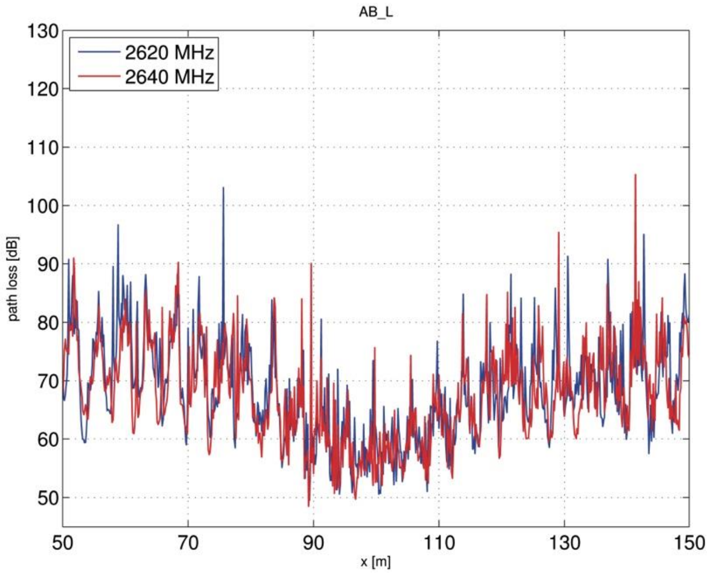

Figure 3-9: Rx Power for AB_L antenna.

Although there is an important difference in the received power for the two 20 MHz spaced subcarriers, both follow a similar trend. The body dynamics have a strong impact on the overall channel performance, and, due to the strong variations in antenna orientation, the received power varies up to 15 dB during one running period.

3.2.1.4 Achievements and planned activities

Three institutions have been involved in this JRA, INOV (Carla Oliveira, Michał Maćkowiak and Luis Correia), UPC (Màrius Caus and Ana I. Pérez Neira) and PUT (Hanna Bogucka, Adrian Kliks and Paweł Kryszkiewicz). During the first year of the project researchers from INOV concentrated in the modeling of Body-Area-Network channel, where the antennas mounted on human body can be treated as the virtual MIMO system; in that context PUT researchers work on finding the appropriate link adaptation algorithms that could be applied in such a scenario. Next, both UPC and PUT representatives worked on the influence of applied precoders/equalizers on the average transmit power in FBMC systems. In the context of BANs no paper has been submitted in the first year of the project lifetime, whereas referring to the FBMC systems the scientific visit of Marius Caus has been organized which will focus on the journal paper preparation.

All of the researchers have significant experience in the field of BANs, MIMO, link adaptation and FBMC systems, however all of the problems investigated during the first year of the project originated in the project lifetime. The common work on the input to the state-of-the art section in the first deliverable helped a lot in the definition of the joint research activities initiated in the reporting period of the project lifetime. All institutions contributed to the present deliverable. As the task leader PUT was also responsible for overall formating of this contribution.

There is also a plan for inter-track activity related to the JRA 1.3.2.A. It is planned to do the hardware implementation on the CTTC hardware and verify if the algorithm developed for MIMO-FBMC systems are valid. This initiative is currently ongoing. Moreover, it is planned to use real channel measurements for body area networks that could be delivered from the University of Bologna.

The following papers have been produced:

- Màrius Caus, Ana I. Pérez Neira, Adrian Kliks, “Characterization of the effects of multi-tap filtering on FBMC/OQAM systems”, submitted to the EURASIP special issue on Advances in flexible multicarrier waveforms for future wireless communications (UPC, PUT): The joint work focused on the study of FBMC systems based on the OQAM (FBMC/OQAM). In this context, it is well-known that multipath fading induces ISI and ICI. To eliminate the interference the channel has to be counteracted either at transmission or at reception. In both cases, the processing is based on multi-tap filtering if the channel is highly frequency selective. Although this approach increases the resilience against multipath fading it may increase the average transmit power or the variance of the noise. The work presented in this paper conducts a theoretical analysis to characterize the detrimental effects as a consequence of applying multi-tap filtering.

- Màrius Caus, Ana I. Pérez Neira, Marco Moretti, "SDMA for FBMC with block diagonalization", IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC), June 2013 (UPC): The paper deals with the design of MIMO precoding and decoding matrices when the FBMC based on OQAM (FBMC/OQAM) is applied to multiuser-MIMO channels. It has reviewed the block diagonalization (BD) concept, which was originally devised for OFDM modulation schemes. The technique proposed in this paper shows that it is possible to achieve interference-free data multiplexing in the FBMC/OQAM context, by following the BD idea. Then, FBMC/OQAM remains competitive with OFDM, while it provides spectral efficiency gains.

Since current work seems to be very promising and fruitful, it was decided to further strengthen the collaboration in various areas. First, with the aim of establishing a connection between the Task 1.3.2: Low-interference, low-emission, radio interfaces and the Task 1.3.3: Resource Allocation for optimized radio access, it has been proposed to study the radio resource management problem for FBCM/OQAM systems. The emphasis will be placed on margin minimization or rate maximization problems given quality of service constraints. The starting point of this activity will be the paper "SDMA for FBMC with block diagonalization". Therein, it is demonstrated that several users can be served in the same time slots and frequency resources in the absence of interference. However, it is mandatory that the same users are allocated on adjacent subcarriers in order to avoid inter-user interference. This observation highlights that subcarriers have to be assigned to users in a block-wise fashion in order to benefit from the technique presented in the paper. Hence, existing strategies will be revisited to be applied in scenarios where the band is partitioned into resource blocks, instead of individual subcarriers. The people who will participate in this task are: Màrius Caus, Ana I. Pérez Neira, Adrian Kliks and Marco Moretti.

Furthermore, it is planned to put more effort on the virtual MIMO systems in the BAN scenario, exactly to verify the performance of the various link adaptation algorithms applied for multi antenna BAN systems. Two scientific visits are planned, first Michał Maćkowiak from INOV is planning to visit PUT in the first part of the second NEWCOM# year, and later the re-visit is planned in Lisbon in the second year of the project. Let us underline that this work seems to be of high interest for the future project that could be realized in the Horizon 2020.

3.2.2 <u>JRA on advanced filtering and adaptive signal processing (OOB, PAPR, SIC)</u>

Leader: Pawel Kryszkiewicz (PUT)
Main partners: Adrian Kliks and Paweł Kryszkiewicz (PUT), Yves Louet and Amor Nafka (SUPELEC)

3.2.2.1 Description

The goal of this JRA is the investigation of advanced filtering and signal processing algorithms for interference minimization in multicarrier systems. In the consecutive sections, the detailed analysis of the achieved results for PAPR and OOB reduction in OFMD scheme are provided. The expected outcomes and analysis of the future work is also included.

The proposed work targets to investigate PAPR reduction capability in NC-OFDM systems. Indeed wireless communication systems based on OFDM have a potential of achieving high spectrum efficiency. Unfortunately, OFDM-based signals suffer from the high out-of-band emission, thus dedicated spectrum shaping algorithms are usually applied in order to ensure required protection level for the neighboring transmission that is important e.g. in cognitive radio applications. Application of such algorithms is particularly crucial in NC-OFDM systems, in which a portion of the inner subcarriers is switched off allowing other systems (e.g. the licensed ones) to occupy that frequency band. In both cases, i.e. OFDM or NC-OFDM transmission, high envelope variations of time-domain signals, expressed typically in form of the peak-to-average power ratio (PAPR), causes intermodulations on a vast number of frequencies while passing through nonlinear elements such as power amplifier (PA). Additionally, the application of rectangular time-domain pulses for carrying user data results in sync-shaped subcarrier spectrum. One can notice the presence of the specific effect, called hereafter as out-of-band (OOB) radiation, in which subcarrier spectrum sidelobes (SSS) add to the intermodulation distortions (IMD). It can be seen as a main source of interference induced to the adjacent system. Some dedicated subcarriers can be sacrificed in NC-OFDM spectrum to overcome these problems. In the context of PAPR mitigation such an approach is known as the tone reservation (TR) technique, while in the second case, for IMD power reduction, these tones are called cancellation carriers (CC). Although both algorithms address different problems, the power spectral density (PSD) functions observed at the output of PA after application of those algorithms confirm OOB power improvements. It is therefore reasonable to combine both approaches to minimize resultant OOB radiation regardless of its source. Although a combination of both methods has already been proposed different subcarriers were used for CCs and TR algorithms, resulting in a weak OOB radiation reduction. Furthermore, both algorithms were used “serially”, i.e. the TR method was followed by CC algorithm, as authors claimed CCs do not increase PAPR value. Though, it has already been shown that unwanted PAPR increase caused by CCs insertion can be observed.

As a conclusion, one of the JRA objectives is to design a low-complex algorithm for reduction of OOB radiation observed after power amplifier regardless of its origin. Another issue to investigate in this JRA is to study how PAPR parameter can be expressed in the frequency domain. By definition, PAPR is the ratio of the maximum instantaneous power to the mean power, both described in the time domain. Nevertheless, it could be of great use to estimate PAPR considering only frequency samples of OFDM signal. To the extent that OFDM signal is filtered (what implies peak re-growths), that tone reservation is a very popular PAPR reduction method (tones are added in the frequency domain), it is timely to get a frequency vision of PAPR.

3.2.2.2 Adherence and relevance with the identified fundamental open issues

Following the open issues listed in section 2.2.3.2, PAPR reduction in NC-OFDM systems considering Out of Band reduction capabilities has been identified as a major problem in this JRA. NC-OFDM systems have attracted considerable attention recently especially in cognitive radio scenarios, ADSL or smart grids in which frequency bands are not contiguous anymore and in which spectrum masks requirements are very severe. So a trade-off between PAPR reduction and adjacent spectral re-growth has to be found.

3.2.2.3 Initial results

Regarding the issue on PAPR and OOB, a method to mitigate out-of-band radiation in NC-OFDM systems which are highly prone to intermodulation and sensitive to nonlinear operation has been investigating. The idea is to use same set of carriers for joint IMD and SSS reduction. Based on the obtained initial results it is apparent that it is possible to merge the two approaches, used traditionally separately for PAPR and SSS reduction, and minimize the OOB radiation in a computationally efficient manner.

In the coming months results will be provided about the proposed method for PAPR reduction and OOB trade-off in NC-OFDM systems. Furthermore, the detailed analysis of the PAPR coefficient distribution in the context of non-contiguous systems will be considered. It is also planned to concentrate the work on the hardware implementation of the OOB reduction algorithms in the NC-OFDM scenario.

3.2.2.4 Achievements and planned activities

Two institutions have been involved in realization of this JRA, PUT (Adrian Kliks and Paweł Kryszkiewicz), and SUPELEC (Yves Louet and Amor Nafka). All representatives have been actively participated in the joint work on finding the optimal PAPR and OOB reduction method. The whole work done in this JRA was originated and realized during the first year of NEWCOM# project. The common areas of interest for joint collaboration have been identified based on the numerous teleconferences organized during the reporting time. Also the effort put on the prepareation of the contribution to the state-of-the-art section in the area of the first report helps in identification of the common research directions. Both partners have significant experience in various research areas (PUT in in spectrum shaping, sidelobes supression, various multicarrier schemes, and SUPELEC in PAPR reduction, multicarrier systems) and the possesed knowledge has been used to solve the newly-established investigation problem. The joint investigation problem was defined at the very beginning of the project lifetime and resulted in the publication that focuses on development of low complex method for reduction of both intermodulation and subcarrier spectrum sidelobes presented. Based on that the optimization problem has been identified and solved analytically; the obtained results allowed for definition of the low-complex, thus practically applicable algorithm for joint reduction of PAPR and OOB, or more precisely, the intermodulation effects and subcarrier spectrum sidelobes.

Details of the publication are as follows: Kryszkiewicz, P.; Kliks, A.; Louet, Y., "Reduction of subcarriers spectrum sidelobes and intermodulation in NC-OFDM systems", 2013 IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Oct. 2013 (PUT, SUPELEC).

Both institutions have contributed to the deliverable. As the task leader, PUT was also responsible for overall formating of this contribution.

There exists already strong relationship with the Track 2, mainly with the WP21 and JRA on Enhanced NC-OFDM transmission with reduced spurious emission level. So far the detailed measurements of power amplifier characteristic in practical system (USRP) have been done and used in analysis done in JRA 1.3.2.B in order to verify if there is a possibility of on-line consideration of Power Amplifier characteristic in the developed algorithm for OOB reduction.

Based on the achievements done in the first project year, the researchers from both institutions plan to further strengthen the collaboration. There are various activities that are considered for joint work, which are listed below, and can act as the tentative plan for the remaining two years of the project lifetime:

- The scientific visit of Yves Louet in Poznan is planned (February 2014). The goal of the visit is to work on theoretical analysis of the PAPR metric in generalized multicarrier systems and to focus on the joint algorithm for power amplifier linearization and OOB reduction with the constraint of keeping the energy efficiency of the power amplifier as high as possible.

- It has been specified that three main directions of joint investigation will be further continued, these are listed below:

a. Joint work on the analytical derivation of the PAPR and OOB metrics distributions.

b. Joint work PAPR and OOB reduction algorithms in the non-contiguous OFDM/FBMC systems.

c. The work on the joint power amplifier linearization and OOB reduction approaches; the goal is to maximize the power amplifier energy efficiency with the constraint put on the error-vector-magnitude, adjacent channel power ratio and overall complexity.

- It is planned that Marwa Chafii from SUPELEC will visit Poznan in May/June 2014 in order to work on the PAPR issues focusing on finding new orthogonal basis (other than complex exponential) that will have better PAPR characteristics.

- Finally, it has been agreed that depending on the availability of human resources there will be some attempts to implement selected OOB and PAPR reduction algorithms in USRP.

3.3 Task 1.3.3: Resource Allocation for optimized radio access

Task Leader: Luca Sanguinetti (CNIT)

The Task is devoted to the investigation and development of energy-efficient algorithms and schemes for controlling interference in HetNets (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. In addition to this, mechanisms and schemes that introduce incentives for opportunistically exploiting the unused access capacity of different network tiers will also be adopted and investigated. Based on the experience of the partners involved in this task, three different JRAs have been identified:

- JRA on interference management techniques for heterogeneous networks

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

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

3.3.1 <u>JRA on interference management techniques for heterogeneous networks</u>

Leader: Jordi Pérez-Romero (UPC)
Main partners: Jordi Pérez-Romero, Katerina Koutlia and Ramon Agusti (UPC), Andreas Zalonis, Nikos Dimitriou and Andreas Polydoros (IASA), Adrian Kliks, Paweł Kryszkiewicz and Hanna Bogucka (PUT), Lila Boukhatem, Steven Martin and Tara Ali Yahia (CNRS/UniPS)

3.3.1.1 Description

The main objective of this JRA is to propose solutions to the interference management problem in HetNets. As identified in several references in section 2.3.1 this problem is critical due to various aspects such as unplanned deployment, CSG access to femtocells, power differences between nodes, high dynamism associated to traffic and user locations, etc. In this context, specific goals of the interference management solutions are: (i) ensure that Quality of Service (QoS) requirements of the different terminals in the scenario are fulfilled, (ii) ensure 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, and (iii) minimize energy consumption. OFDMA-based systems such as LTE-A can be considered as the basis for joint investigation, while other systems such as WiFi can also be considered for traffic offload.

Different optimization problems can be considered depending on the resource to be managed: (i) transmit power optimization, (ii) frequency assignment optimization, including the particular case of having some bands (e.g. TVWS) that can be used opportunistically depending on their availability, (iii) temporal dimension (Almost Blanc Subframes), and (iv) User/cell association optimization (Cell Range Expansion thresholds). Herein, specific activities of the JRA in some of these dimensions are discussed along with some initial results.

3.3.1.2 Adherence and relevance with the identified fundamental open issues

In the following a description of the considered open problems in this JRA is given, taking into consideration the detailed SoA analysis presented in section 2.3.

Enhanced power adjustment strategies based on environmental/context knowledge

One objective of this joint work is to take advantage of the users' location and mobility knowledge in the design and the optimization of new power adjustment techniques. Victim MUEs locations and their respective mobility can significantly help in achieving smarter and more accurate adjustments of LFNs transmission power through a better handling of the interference dynamics. To meet this objective, we aim at exploiting several tools such mobility prediction and rich context information stored in databases such as REMs (Radio Environment Maps) [237]. As discussed in section 2.3.3.3, environment-related rich context information (nodes location, propagation models, etc.) used in LPN power control schemes may be inaccurate or outdated. The impact of those inaccuracies in the proposed algorithms should be investigated. The efficiency of spatial and temporal interpolations will also be studied.

Optimized resource allocation in HetNets for inter-cell interference coordination

The purpose of this activity is to perform an optimization of (i) the different frequency bands assigned to the existing cells in a HetNets scenario, (ii) the amount of Almost Blank Subframes (ABS) used by each cell in the time domain, (iii) the cell range expansion parameter governing the user-to-cell association. Thus, the activity covers the problems identified in the state-of-the-art sections 2.3.3.1, 2.3.3.2, and 2.3.3.4. The target will be to minimize the intercell interference or to maximize the available capacity.

Focusing on the SoA analysis performed in section 2.3.3.2 regarding frequency domain intercell interference coordination, it has been observed that most of the existing works are considering fixed patterns for fractional frequency reuse, which may not be adequate when considering irregular deployments or non-homogeneous traffic distributions. Moreover, there are few works that have addressed the development of this type of schemes in heterogeneous scenarios involving both macro and small cells. Correspondingly, a first objective of this activity will be to contribute to the definition of an optimized strategy that considers both the macro and small cells.

Similarly, focusing on the joint optimisation of ABS and CRE, as discussed in 2.3.3.4 there is still a small number of works that have addressed this problem, whose optimum has been identified as computationally hard [213]. Thus, this activity will try to contribute by developing new optimized solutions for this joint setting in order to minimize the interference generated between macro and small cells. The progress in this activity will be organized in different stages, starting first by the optimisation of the frequency assignment, and then considering the joint optimisation of ABS and CRE.

The starting point for the frequency assignment problem will be a Gibbs sampler-based mechanism [214], [215] with the target of minimizing the global interference. The rationale behind this selection is that this mechanism accomplishes such an interference minimization in a natural way.

Strategies for allocating shared spectrum in HetNets

As it has been stated in the SoA analysis in section 2.3.4, the use of shared spectrum such as TVWS to extend the capacity in LTE or LTE-A networks is seen as particularly relevant in the case of small cell scenarios, thanks to the more reduced coverage area and power levels of small cells, which makes easier the task of finding a sufficiently large TVWS to ensure the desired coverage. However, there are actually still very few works that have addressed the problem of how to allocate TVWS spectrum in an optimized way when small cells are considered.

In this context, this activity intends to contribute to this field by proposing smart optimized strategies to perform TVWS assignment in a HetNet scenario. In particular, a mobile operator in a certain geographical area will be considered, with a network consisting of both macro cells and small cells. The operator has a licensed spectrum to be allocated to the different cells. Moreover, to handle traffic increase situations in certain areas and at certain times, the operator may decide to make use of additional shared spectrum. Then, the activity needs to properly identify the amount of additional spectrum needed and to devise strategies to decide which is the most appropriate spectrum to be assigned to each cell taking into consideration the interference generated to/from the primary and to/from other secondary users.

Mapping to open issues

Based on the above considerations, and in relation to the SoA analysis in section 2.3, this JRA covers the following open issues:

- Efficient power adjustment techniques for reducing the interference between macro and small cells making use of context information stored in databases such as REMs: In particular, the impact of accurate, inaccurate and/or outdated information on the system performance remains as an open issue to be investigated, as well as the efficiency of spatial and temporal interpolations.

- Optimize the frequency domain intercell interference coordination for heterogeneous scenarios with both macrocells and small cells: This will be done by smartly allocating channels to cells by that taking into consideration irregular deployments or non-homogeneous traffic distributions, so that classical fixed fractional frequency reuse patterns become inefficient.

- Joint optimization of ABS and CRE parameters in heterogeneous networks: As previously discussed there is still a very reduced number of works that have addressed this problem, whose optimum has been identified as computationally hard, so this activity will try to contribute to develop new optimized solutions for this joint setting in order to minimise the interference generated between macro and small cells.

- 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 in way. This JRA will try to contribute with new optimized solutions to this problem.

3.3.1.3 Initial results

Enhanced power adjustment strategies based on environmental/context knowledge

One of the most challenging interference scenarios in two-tier networks is the interference caused by a small cell (e.g. FAP) to a nearby macrocell user (MUE) in the case of shared spectrum and closed access small cell (Figure 3-10). One approach to control this type of interference is to apply on the FAP a power control mechanism based on the detection of ‘victim’ UEs in the area. The objective is to provide protection to the MUEs against FAP interference while maintaining acceptable FAP performance. Traditional optimization algorithms use information collected from the users (through a feedback mechanism) or static network planning information. A new approach is for the terminals and APs to exploit additional environmental and available context knowledge. The REM concept [237] has been proposed as an integrated database that collects and stores various types of information and data models such as geolocation data, propagation models, interference maps, available services, spectral usage regulations, locations and activities of radio nodes, user and service policies. This amount of diverse context information offers opportunities for a more efficient allocation of the available radio resources among the users and more effective interference control. Different instances of the REMs with different types of information can be stored at various levels of the network infrastructure [238] (e.g. in the FAP, the MBS, or a dedicated controller). The challenge resides in the exploitation of the REM context information for the development of pragmatic IM and RRM algorithms by keeping the complexity as simple as possible.

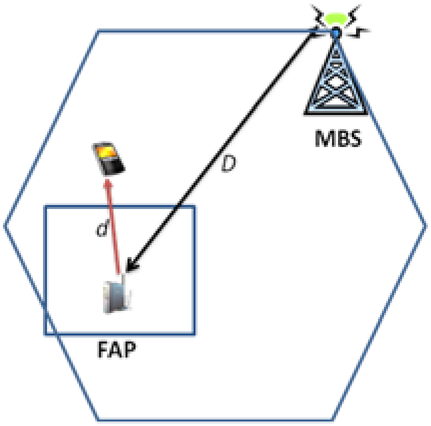

Figure 3-10: Interference scenario

The idea of using knowledge other than classical feedback information was initially exploited in [236] for transmit power adjustment of a closed access FAP based on the existence of a nearby MUE. It was proposed that the FAP will be able to monitor the uplink channel and thus detect UL transmissions from nearby macrocell UEs. Based on that detection, a baseline power control scheme was proposed for LTE femtocells which can be summarized as follows:

- The FAP measures the Reference Signal Received Power (RSRP) and the SINR from the MBS and neighboring FAPs.
- Upon the detection of a neighboring victim MUE, the FAP reduces its transmission power aiming to maintain a predefined SINR target for the MUE. The algorithm in the FAP assumes that the FAP and the MUE measure the same RSRP from the MBS and that the path loss distance between them has always a specific value (80dB).
- In case the target cannot be achieved, the FAP transmits at a predefined minimum power level.

This algorithm has been shown in [236] to reduce MUE outage with respect to the case when the existence of a neighborhood victim MUE is unknown.

In [203] it was shown that the existence of a local REM can enhance the performance of this algorithm by taking into consideration richer context information such as the positions of the network elements (UEs, FAPs and MBSs) and the environment characteristics of the area (e.g., path loss and shadowing models). In this case the FAP has the necessary information to accurately estimate the expected SINR of the victim MUE. This performance gain can be viewed as an upper bound for pragmatic REM-based algorithms, considering that the inaccuracies in the stored REM data will result in reduced performance. In the context of this activity these inaccuracies will be taken into consideration will be further investigated in order to end up with more pragmatic algorithms.

In another approach which takes into account the context knowledge, a centralized method for power allocation in a mobile user environment is proposed. This strategy intends to give the priority to MUE users in a scenario where macro/femtocells are collocated together using a power adjustment strategy of FBSs while maintaining the communications quality of FUEs. The adopted mechanism exploits the information about the location of MUE users and the number of affected FUEs, i.e. those who will experience a channel quality under the minimum target SINR, due to the power adjustment strategy. Note that the channel quality of FUE does not depend only on the interfering MUEs and the new FBS transmission power, but also on their respective positions and mobility within their coverage area.

Under above considerations, the strategy suggests allowing the FBS to return back an “Objection” report to the MBS in case the requested power adjustment is causing significant degradation to a large number of its users. Moreover, to alleviate the signalling exchange between the macro and femtocells, a new signalling mechanism is proposed in which RSS measurement reports are sent only if a significant change in the received signal values is observed. To do so, the MBS stores in a REM database the last values of the received RSSs while at the FBSs side the same power allocation is maintained until a new explicit RSS measurement report is received.

The performance evaluation of this power allocation strategy has shown an interesting gain in the average throughput of MUE users while maintaining the FUE users performance above a minimum service quality. The study have confirmed the results under service differentiation assumptions (VoIP, video, and CBR flows) and for different scheduling mechanisms. The benefit of the signalling reduction strategy can be observed in Figure 3-11. The number of Measurement Reports (MR) sent by the MBS is reduced especially for high mobility scenarios.

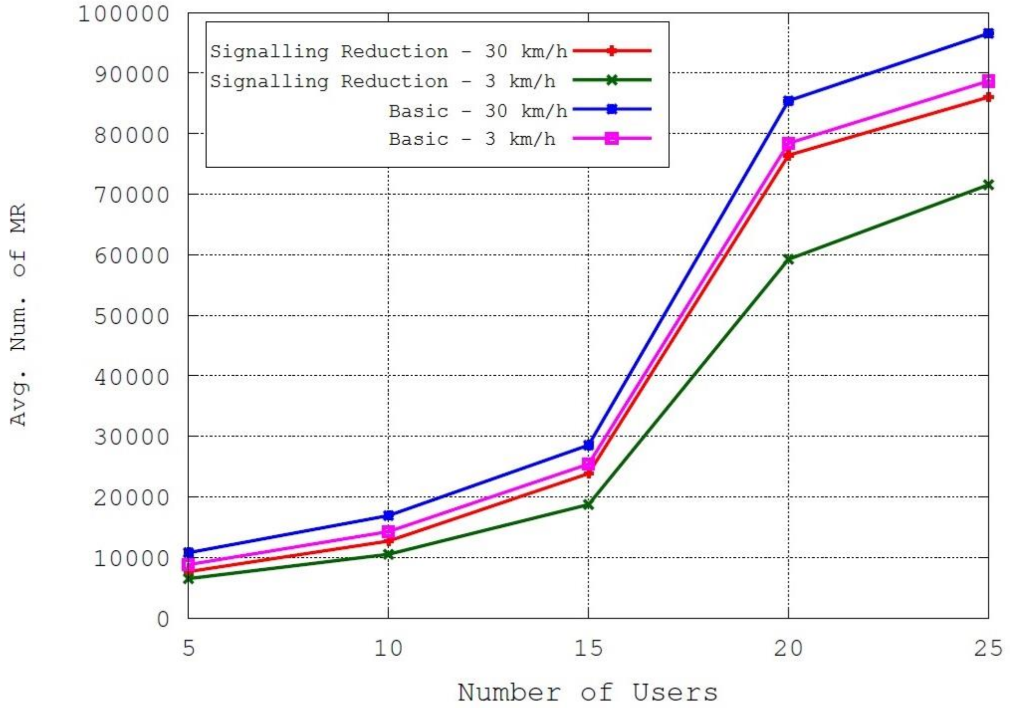

Figure 3-11: Number of MR messages for different mobility profiles

Both the abovementioned examples illustrate an ideal case where the used context information (MBS and FAP location, MUE detection and location, propagation losses) for the adjustment of the FAP transmission power is accurately known. Pragmatic context-aware power control algorithms should also take into consideration the possible errors in the position estimation of the network elements and the uncertainty in the calculated path loss and shadowing terms that are used in the FAP transmit power calculation. The scope in this activity is to investigate the effect of such inaccuracies in proposed power adjustment algorithms.

Optimized resource allocation in HetNets for inter-cell interference coordination

As previously discussed, an initial approach that will be considered for the optimisation of the spectrum assignment will be based on a Gibbs sampler approach, with the main objective of minimising the generated interference. For that purpose, in the following the applicability of Gibbs sampler approach will be first formulated for a PFR scenario involving only macrocells, so that this will be further extended to include also small cells.

Under the above considerations, the proposed approach intends to perform dynamic channel allocation with the target of mitigating ICI in the DL of a cellular system where N Base Stations are spatially divided in three sectors (cells) with the use of directional antennas, resulting in a set of X cells. Users are randomly distributed in the scenario and associated with the cell with which they experience the minimum total propagation loss that takes into consideration both the shadowing and the antenna pattern, as follows:

Let U_x be the set of users associated to cell $x \in X$. This set is further split into sets $U_{x,in}$ and $U_{x,out}$ corresponding to the users of the inner and outer parts, respectively. A user is in the inner part if the total propagation loss to cell x is below a certain threshold L_{th}. Otherwise, it is in the outer part.

Let us consider a set of C frequency channels or sub-bands to be shared among the set of X cells. The bandwidth of each channel $c \in C$ is B_c. For simplicity reasons we assume that each cell can be assigned only one channel for the inner part and another one for the outer part; however this work can be easily extended to assign a group of frequencies to each cell. Moreover, let us define as $C_{in} \subseteq C$ and $C_{out} \subseteq C$ the subsets that contain the channels that can be assigned to the inner and the outer part of the cells, respectively. Note that in general we do not force C_{in} and C_{out} to be disjoint sets, thus having the flexibility to allocate in some cases the same channel to the inner and outer parts of the cell.

Based on the above, at a given point of time each cell x is characterized by its state $c_x = (c_{x,in}, c_{x,out})$ that is given by the channel $c_{x,in} \in C_{in}$ assigned to the inner part and the channel $c_{x,out} \in C_{out}$ assigned to the outer part.

In turn, the transmit power of a given cell x in channel c is $P_{x,out}$ if the channel is allocated to the outer part, $P_{x,in}$ if the channel is allocated to the inner part (and not to the outer) and 0 if the cell does not use the channel.:

The target of the proposed optimization approach is to minimize the overall inter-cell interference. For that purpose, we define the *global energy* to be minimized as the total interference of the network which will be the sum of the total noise and the interference measured by all the cells:

$$\varepsilon = \sum_{x} \left[P_N + \frac{1}{|U_{x,in}|} \sum_{u_{x,in}} \sum_{k \neq x} \frac{P_{k,c_{x,in}}}{L_{u_{x,in},k}} + \frac{1}{|U_{x,out}|} \sum_{u_{x,out}} \sum_{k \neq x} \frac{P_{k,c_{x,out}}}{L_{u_{x,out},k}} \right] \qquad (3.3.1.1)$$

where P_N is the noise power and $L_{u_x,k}$ respectively denote the Path Loss of user u_x with the interfering cell k. By applying some simple mathematical manipulations to the above expression, it is possible to optimize the above energy function by making use of a distributed Gibbs sampler approach. The objective of the Gibbs Sampler is to find the states c_x (channel allocation) for each cell that minimize the following local energy for each cell x [214][216]:

$$\varepsilon_x\left(c_{x,in}, c_{x,out}\right) = P_N + \sum_{k \neq x} \left(\frac{1}{|U_{x,in}|} \sum_{u_{x,in}} \frac{P_{k,c_{x,in}}}{L_{u_{x,in},k}} + \frac{1}{|U_{x,out}|} \sum_{u_{x,out}} \frac{P_{k,c_{x,out}}}{L_{u_{x,out},k}} \right) + \sum_{k \neq x} \left(\frac{1}{|U_{k,in}|} \sum_{u_{k,in}} \frac{P_{x,c_{k,in}}}{L_{u_{k,in},x}} + \frac{1}{|U_{k,out}|} \sum_{u_{k,out}} \frac{P_{x,c_{k,out}}}{L_{u_{k,out},x}} \right)$$

(3.3.1.2)

The *local energy* function actually includes the measurement of the interference that users of cell x will experience from the other cells if cell x state is c_x (second term of the equation), as well as the interference that cell x will cause to the neighboring cells (third term of the equation).

The minimization of the *energy function* given by (3.3.1.1) is achieved by means of the execution of the procedure indicated in Algorithm 1 at each cell. Assuming that the system starting time is *t*=0, each cell is assigned with an exponentially distributed timer with mean t_a. When a cell's timer expires, the algorithm is executed and the channel selection (i.e. the cell state c_x) is carried out by sampling a random variable λ using the following probability distribution that represents the probability of selecting state c_x among the set of all possible states denoted as C_S.

$$\pi(c_x) = \frac{e^{\left(-\varepsilon_x(c_{x,in}, c_{x,out})/T\right)}}{\sum_{c' \in C_S} e^{\left(-\varepsilon_x(c'_{x,in}, c'_{x,out})/T\right)}} \quad (3.3.1.3)$$

where T is the *temperature* parameter and is calculated as:

$$T = \frac{T_0}{\log_2(2+t)} \quad (3.3.1.4)$$

In this formula T_0 is a constant and t is the age variable representing the time passed since *t*=0. After each channel selection is performed for a given cell, a new timer is generated to schedule the subsequent execution of the algorithm. The probability distribution described above favors the lower energy states and with $T \to 0$ it will converge to a steady state that minimizes the *global interference*.

Algorithm 1: Gibbs Sampler Procedure

1: ***if*** *cell x timer (T_x) expires at time t*

2: *calculate the temperature parameter* T (3.3.1.4)

3: ***for*** *each state* $c_x \in C_S$

4: *calculate the Local Energy* $\varepsilon_x(c_{x,in}, c_{x,out})$ (3.3.1.2)

5: *calculate the Selection Probability* $\pi(c_x)$ (3.3.1.3)

6: ***end for***

7: *sample a random variable* λ *with law* $\pi(c_x)$

8: *assign channels* $(c_{x,in}, c_{x,out})$ *according to the outcome of* λ

9: *sample an exponential random variable* μ *with mean* t_a

10: *assign a new timer* ($T_x=t+\mu$)

11: ***end if***

To illustrate the performance of the considered algorithm, the cellular deployment depicted in Figure 3-12 is considered. It consists of 4 tri-sectorial base stations thus having a total of 12 cells, as. The set of frequencies that can be allocated to the outer part is $C_{out}=\{f_0,f_1,f_2,f_3\}$, while for the inner part we assume that just frequency f_0 can be allocated, i.e. $C_{in}=\{f_0\}$. Under this assumption, and despite of the fact that the proposed formulation is general to select either the channel of the inner and/or the outer part, for simplicity we have limited the algorithm to decide only the assignment of the channel in the outer part of the cell, while the channel of the inner part is always fixed. The frequency assignment shown in Figure 3-12 illustrates the classical PFR case where no Gibbs sampling algorithm is used, which is used as a reference for the comparison. Moreover, for the Gibbs sampler-based algorithm it is assumed that the initial allocation considered in the beginning of each simulation is also the one shown in Figure 3-12.

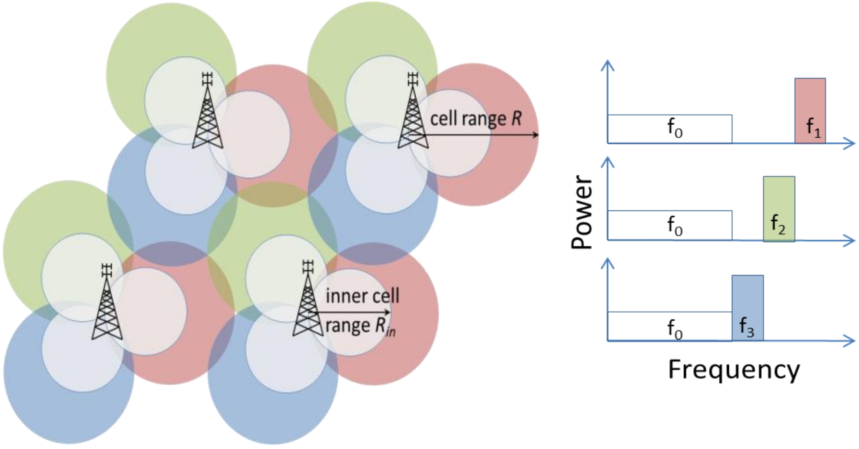

Figure 3-12: System topology and frequency assignment for the reference case

Each cell serves 10 users uniformly distributed in a circular area with range *R*=1 *km* (see Figure 3-12). The total simulation time is $12000 \cdot t_a$ and the simulation step is $t_a/24$. T_0 is set to 0.2 and the energy values in (3.3.1.2) are given in dBW. Simulations are performed for different values of the inner cell range R_{in}. The outer transmit power ($P_{x,out}$) is kept constant to 43 dBm in all the simulations, while the inner transmit power ($P_{x,in}$) is set according to the inner cell range in order to have the same average received power level for an outer user located at a distance *R* and for an inner user located at a distance R_{in}.

The distance-dependent propagation model is 128.1 + 37.6 log d(km), a shadowing with 10 dB standard deviation is considered, and the antenna pattern assumes horizontal beamwidth 120º, vertical beamwidth 70º and backward attenuation 70 dB. The noise power is -100 dBm and the bandwidth of each channel is 5 MHz.

In Figure 3-13 we present the reduction of the energy function (i.e. the reduction in interference) achieved by the Gibbs-sampler mechanism with respect to the reference scheme, for the inner and the outer users separately. Since the algorithm is applied only to modify the frequency assigned in the outer part it is clearly seen that only the energy of the outer users is improved, especially for high inner cell ranges, in which a significant reduction is achieved. Moreover, for inner cell ranges below 300m approximately, a loss in the energy of the inner users can be observed. The reason is that for these inner cell ranges the algorithm assigns also frequency f_0 to the outer part in some cells, which may result in more interference for the inner users. Nevertheless, since for small inner cell ranges the number of inner users is reduced, this slight interference increase does not have a significant impact when compared with the benefit achieved by outer users.

The benefits of the proposed PFR algorithm also include the capacity improvement. This can be observed in Figure 3-14 that shows the average capacity for the users located at the cell edge, which are those more sensitive to ICI. For this computation, users are considered to be at the cell edge if they are located at a distance above 0.9*R* (note that edge users can be outer or inner users depending on the considered inner cell range in each simulation). The figure reflects a significant capacity improvement brought by the Gibbs-based strategy with respect to the reference scheme, with an average gain of 12% and a maximum gain up to 20% (for the inner range of 100 m), thanks to the ICI reduction brought by the proposed approach. In turn, Figure 3-15 shows the comparison in terms of the average capacity per user taking into consideration all the users in the cell. In this case, the overall capacity improvement brought by the Gibbs-based strategy is more reduced, with an average gain of 4% and a maximum of 11%, occurring also for the inner cell range of 100 m.

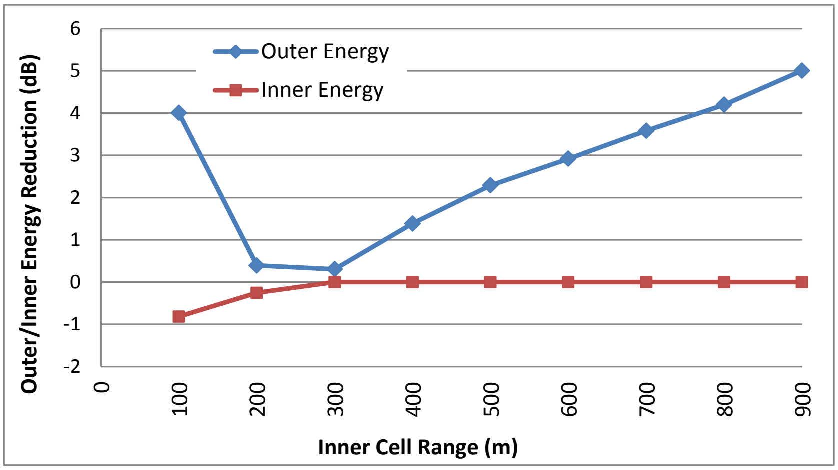

Figure 3-13: Inner and Outer energy reduction

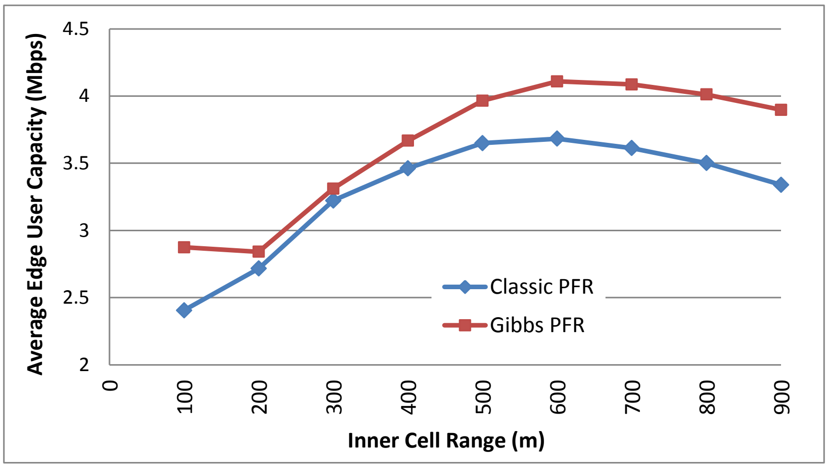

Figure 3-14: Edge User average Capacity

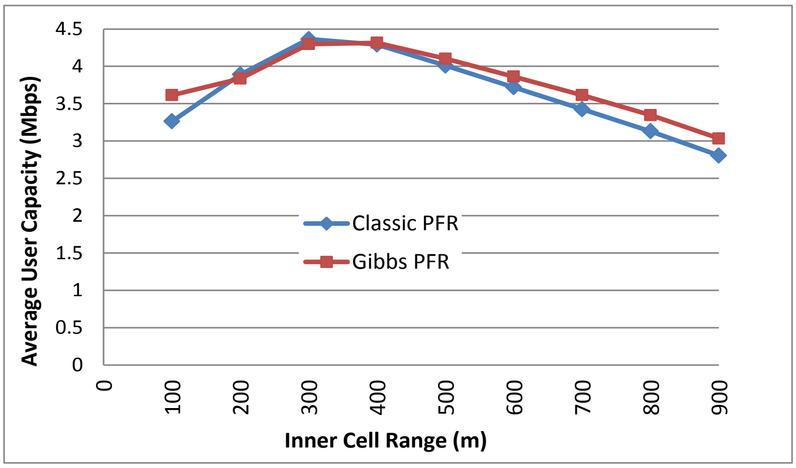

Figure 3-15: Average User Capacity

The initial results presented in this section have revealed the capabilities of the Gibbs sampler based mechanism to optimize the frequency assignment for interference coordination based on PFR in macrocell scenarios. Based on the promising results obtained, the next step will be the formulation and evaluation of the algorithm in case that both macro and microcells are present in the scenario.

3.3.1.4 Achievements and planned activities

The collaborating partners in this activity are UPC (Jordi Pérez-Romero, Katerina Koutlia, Ramon Agusti), IASA (Andreas Zalonis, Nikos Dimitriou, Andreas Polydoros), PUT (Adrian Kliks, Paweł Kryszkiewicz, Hanna Bogucka), CNRS/UniPS (Lila Boukhatem, Steven Martin, Tara Ali Yahia). In the framework of this JRA, the first task has been the identification and classification of relevant problems for the interference minimization in HetNets, together with a SoA analysis to identify open issues. For that purpose, a taxonomy of different techniques was performed, including techniques in the time domain, in the frequency domain, in the power domain and in the user-to-cell association domain. The outcome of this joint work is reported in this deliverable in section 2.3. The editor of this section was Jordi Pérez-Romero (UPC) and all partners contributed to all the parts of this SoA analysis.

In addition, each partner has exchanged the individual works carried out in the identified topics in order to get a common understanding that serves as the basis for the future work. This includes the initial results of some individual works reported in this deliverable (section 3.3.1).

The four partners (UPC/IASA/PUT/UniPS) are working now towards a common framework embracing the different techniques taking into consideration that all of them require the use of some type of radio environment information. This framework is based on the Radio Environmental Map (REM) and for that purpose possible REM architectures are being identified including the required parameters by each technique.

UPC and PUT are also collaborating in the use of shared spectrum (e.g. TVWS band) for the deployment of HetNets. The collaboration included: (i) a state-of-the-art survey has been performed (reported in section 2.3), (ii) a framework based on the spectrum broker concept for extending the capacity of HetNets by means of TVWS to small cells, (iii) a map coloring algorithm for deciding the TVWS spectrum assignment to small cells. From an experimental perspective this activity is strongly related with Track 2 (WP2.1, “JRA G: Spectrum Occupation Measurements and Database Exploitation”) in which a measurement campaign of Spectrum occupation in different bands is being performed to be used as input for the theoretical work.

Based on the above-mentioned work and collaborations the following papers were prepared.

- Nikos Dimitriou, Andreas Zalonis, Andreas Polydoros, Adrian Kliks, Oliver D Holland "Context-Aware Radio Resource Management in HetNets", accepted at WCNC 2014 (FutureHetNets workshop), April, 2014 (Joint paper IASA/PUT): The paper provides a concise description of the role of RRM techniques in HetNets by analyzing the criteria and the tradeoffs that are assumed, and presents a framework for the exploitation of the available context information within the HetNet environment, that leads to optimized spectrum usage.

- K. Koutlia, J. Pérez-Romero, R. Agustí, M. Ziak, “On the use of Gibbs Sampling for Inter-Cell Interference Mitigation under Partial Frequency Reuse Schemes”, MOBILITY 2013 conference, Lisbon, Portugal, November, 2013 (Individual paper UPC): This paper proposes a distributed algorithm based on Gibbs Sampling that performs an optimized dynamic channel allocation to mitigate the ICI in cellular scenarios applying Partial Frequency Reuse (PFR). A summary of this paper is included in section 3.3.1 of this deliverable.

- R. Kurda, L. Boukhatem, T. Ali Yahiya, Interference Mitigation in Mobile Environments through Power Adjustment in Macro and Femto cell Systems , accepted at IEEE WCNC 2014, April 2014 (Individual paper UniPS): This paper proposes a centralized power control mechanism for interference mitigation in a mobility environment where macrocells and femtocells are co-located together. The key benefits of this scheme is to achieve higher performance for non-closed subscriber group (CSG) users, as well as avoiding potential service degradation of femtocell users by taking into account mobile users locations and SINR at both macro and femtocell sides. In addition, an algorithm at the network side is proposed to decrease the signaling overload caused by the proposed centralized power control scheme. Simulation results show that the proposals provide a better performance in terms of signaling overhead and throughput of macrocell users while maintaining a high QoS for femtocell users.

Furthermore, the following presentations were given:

- “Interference Coordination techniques for ensuring QoS in heterogeneous networks”, NEWCOM#. Track 1 meeting: Paris 6-7 March 2013. Presenter: Jordi Pérez-Romero (UPC)

- “JRA 1.3.3.A. Interference management techniques for heterogeneous networks”, NEWCOM# Track 1/2 meeting: Lisbon 21-23 January 2014. Presenter: Jordi Pérez-Romero (UPC). Contributors: UPC/IASA/PUT/UniPS

This JRA is strongly related with “JRA G: Spectrum Occupation Measurements and Database Exploitation” of WP2.1 in which a measurement campaign of Spectrum occupation in different bands is being performed to be used as input for the theoretical work on spectrum assignment of TVWS to small cells. Currently detailed indoor measurements in some buildings are being obtained, in order to build an indoor REM from which the maximum allowed transmit powers can be computed. The following joint paper PUT/UPC has been accepted dealing with these measurements: A. Kliks, P. Kryszkiewicz, A. Umbert, J.Pérez-Romero, F. Casadevall, “TVWS Indoor Measurements for HetNets”, accepted at the IEEE WCNC 2014 - Workshop on Interference and Design Issues for Future Heterogeneous Networks, Istanbul, 2014. It is expected that, during the 2nd year results on the small cell deployment making use of the measurement results will be available. Moreover, the possibility to experimentally evaluate the REM by means of USRP platforms is also currently being under consideration.

The partners in this JRA are also participating in the following dissemination activities:

- Organisation of the Workshop “Interference and Design Issues for Future Heterogeneous Networks”, to be held at IEEE WCNC 2014 conference (Istanbul, 6th April 2014). Detailed information can be found at http://www.wcnc-futurehetnets.org/. Chairs: Hanna Bogucka (PUT), Adrian Kliks (PUT), Jordi Pérez-Romero (UPC)

- A Special Issue proposal entitled "Technical Advances in the Design and Deployment of Future Heterogeneous Networks" has been submitted in December 2013 to EURASIP Journal on Wireless Communications and Networking. Editors: Adrian Kliks (PUT), Jordi Perez-Romero (UPC), Lila Boukhatem (UniPS), Andreas Zalonis (IASA)

The next steps envisaged for this JRA include the development of solutions for the three problems identified at high-level in section 3.3.1, namely “Enhanced power adjustment strategies based on environmental/context knowledge”, “Optimized resource allocation in HetNets for inter-cell interference coordination” and “Strategies for allocating shared spectrum in HetNets”. For each of these problems the general plan that will be considered to further develop the elements identified is the following:

- Develop the proper architecture to support the currently identified interference management techniques in HetNets based on the REM concept. Identify the required REM parameters to be included in the local/global REM entities. Expected deadline: End of April 2014. Contributors: UPC/IASA/PUT/UniPS

- Performance evaluation of the currently identified interference management techniques under the selected REM architecture. This should include the effect of inaccuracies in the REM information over the performance, as well as some analysis of the signalling requirements. Expected deadline: End of June 2014. Contributors: UPC/IASA/PUT/UniPS

As a result of the above two outcomes a joint magazine paper UPC/IASA/PUT/UniPS is currently under preparation. Preliminary title: "On the use of Radio Environment Maps for Interference Management in Heterogeneous Networks".

- Definition and evaluation of novel techniques and algorithms for interference management in hetnets, optimizing the frequency/time/power/dimensions, based on the developed REM architecture. This activity is expected to be continued during the 2nd and the 3rd year. Contributors: UPC/IASA/PUT/UniPS

- Evaluation of TVWS assignment techniques for the deployment of small cells in indoor scenarios based on actual measurements. Expected deadline: End of October 2014. Contributors: UPC//PUT.

- 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.

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

Leader: Luca Sanguinetti (Pisa)
Main partners: Luca Sanguinetti, Giacomo Bacci and Riccardo Andreotti (CNIT-Pisa), Veronica Belmega (CNRS-ENSEA), Ivan Stupia (UCL)

3.3.2.1 Description

A detailed description of the scenarios and problems under investigation is given herein.

Distributed energy-efficient power optimization in cellular relay networks

This research activity is focused on developing game-theoretic-inspired power allocation algorithms to improve the relay performance in interference limited cellular systems. The scenario considered is the uplink of an arbitrary hexagonal OFDMA cellular network with at least three cells with frequency reuse factor equal to one. Each cell is divided into an inner and an outer sector. The macro base station is placed at the center of the cell and serves the inner sector, whereas the outer sector is further subdivided into a certain number of adjacent sectors that are served using two different architectures. The first one is depicted in Figure 3-16(a) and refers to a network in which a fixed relay station serves each sector. The second one is shown in Figure 3-16(b) and accounts for a network in which the three adjacent sectors are served by a shared relay placed at their intersection. The shared relay concept was originally proposed in IEEE 802.16m and relies on the idea to place a multiple antenna relay base station at the intersection of two or more cells. The relay decodes the signals from the multiple users in neighboring cells using the multiple receive antennas to cancel interference, and then retransmits the signals to the multiple base stations of different cells using MIMO-based broadcasting methods.

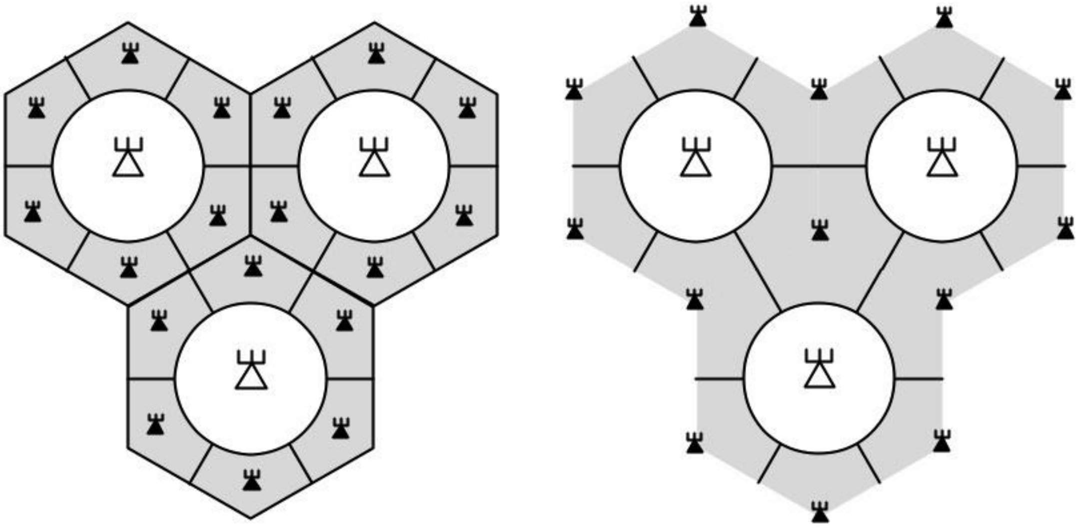

Figure 3-16: Cellular relay network: (a) multiple relay and (b) shared-relay concepts

In both cases, the user equipments (UEs) are assumed to be uniformly distributed within the cell and are equipped with a single antenna. Perfect channel knowledge is assumed at the relays. The communication between the macro base station and the UEs takes place with a single-hop if the UEs are placed within the inner sector, whereas a two-hop protocol is needed if the UEs are within the outer sector. In this latter case, the information first flows from the UE to the closest relay, and then from the relay to the macro base station. We assume that UEs within the same cell make use of sets of orthogonal subcarriers and thus they do not interfere among each other. On the other hand, interference may arise among UEs in adjacent clusters of neighboring cells sharing the same subcarrier. The objective of this research activity is to evaluate the performance in terms of energy efficiency (in terms of bits/joule) of an uplink power control algorithm operating in the two cases described above. Unlike existing solutions, we allow the multiple relays in the former case to cooperate in a distributed manner while satisfying power consumption constraints and quality-of-service requirements.

The main objectives of this research can be summarized as follows:

- Study the solution of the centralized power allocation when relays are able to cooperate;
- Study the solution of the distributed power allocation when the relays do not exchange any information;
- Compare the performance, in terms of energy efficiency, of the two power allocation strategies above, according to the following scenarios:
    - when the number of receiving antennas grows;
    - for different values of circuit power;
    - for different realization of correlation matrices;
    - for different receiver techniques with or without interference cancellation.

From a practical point of view, the above lines of research could provide analytical guidelines for addressing some of the fundamental limits and criteria in the field of cellular network design and implementation, including (i) determining the number of relay base stations and antennas needed for covering a given area; (ii) understanding the required degrees of cooperation among base stations; (iii) better understanding the key parameters in the energy-efficient design of macro-cellular relay-based networks.

Distributed energy-efficient power optimization in HetNets

The objective of this activity lies in finding game-theoretic inspired power allocation algorithms that allow improving the energy efficiency of a two-tier network in which a macro cell coexists with an irregular deployment of small cells cooperating among each other in a distributed manner.

Elaborating on the HetNet scenario described in Section 2.3.1, let us 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 nth subchannel between the transmitter k and receiver i is denoted by $H_{i,k}(n)$. 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 a local transmit power constraint. We assume that the K transmitter-receiver pairs do not cooperate with each other and that no centralized mechanism is used to control the network access. Moreover, we focus on transmission techniques where no interference cancellation is performed and assume that the multi-user interference is simply treated as additive coloured noise at each receiver. Perfect channel state information is also assumed to be locally available at both transmitter and receiver sides. In the above circumstances, the maximum achievable rate on link k for a specific power allocation profile $\mathbf{p} = [\mathbf{p}_1^T, \mathbf{p}_2^T, ..., \mathbf{p}_K^T]^T$ is given by

$$R_k(\mathbf{p}_k, \mathbf{p}_{-k}) = \sum_{n=1}^{N} \log\left(1 + \frac{\left|H_{k,k}(n)\right|^2 p_k(n)}{\sigma_k^2(n) + \sum_{i \neq k} \left|H_{i,k}(n)\right|^2 p_k(n)}\right) \tag{3.3.2.1}$$

where $\mathbf{p}_{-k} = [\mathbf{p}_1^T, \mathbf{p}_2^T, ..., \mathbf{p}_{k-1}^T, \mathbf{p}_{k+1}^T, ..., \mathbf{p}_K^T]^T$ collects all the power allocation vectors, expect the kth one. The study and analysis of NE problem of a heterogeneous multiuser system in which each player (transmitter-receiver pair) aims at maximizing its own rate or energy-efficiency has not been addressed yet in the literature and represents the major contribution of this research activity. To fulfill this lack, the case of competitive players aiming at maximizing their own energy-efficiency is analyzed. Capitalizing on the waterfilling structure of the players' best response of this game, we eventually provide a unified view for the heterogeneous game and model the equilibrium problem as a QVI.

The main objectives of this activity are:

- To investigate the tradeoff between the two conflicting requirements of next generation wireless communications networks: *i*) spectral efficiency; *ii*) energy-efficiency.
- To show that the energy-efficient and the rate maximization problems are nothing else than two instances of a properly defined generalized Nash equilibrium game problem.
- To derive existence and uniqueness results under a unified framework based on quasi variation inequality theory that remain valid for all the possible instances of this general game.
- To design novel distributed algorithm achieving the desired SE-EE trade-off across the entire network.
- Finally, thanks to its generality, the framework developed in this JRA will be then applied to design distributed power control strategies in two-tier networks, wherein small-cells with different coverage and low transmit powers are randomly located in the area covered by the umbrella macro-cell.

Distributed energy-efficient power optimization in BICM-OFDM systems

The main objective of this activity is to derive distributed power allocation approaches, which optimize the energy efficiency of BICM-OFDM systems in the HetNet scenario, accounting for pragmatic design issues such as the use of practical modulation and coding schemes, automatic repeat request (ARQ) mechanisms and packet-oriented transmissions. Users within the same small cell (SC) transmit to the small cell BS (SBS) at the same time and sharing the same band, so that they can cause harmful interference to each other. The assumption is that there is no centralized unit, which assigns transmission resources (TRs) to users within the SC, but rather that users must coordinate among themselves in order to reach a stable configuration of TR. The interest is on distributed power allocation algorithm so that each user maximizes its EE accounting for the interference caused by the other users.

It is worth mentioning 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 EE will depend on the successful transmitted rate, given by the product of the transmission rate and the packet success rate (PSR). As previously described, 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 [264] relies on the theoretical assumption of Gaussian codebooks, whereas in [290] 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 is in fact a “global” metric that cannot be obtained as a linear expression of the successful probabilities of each subcarrier. 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, and the EE of the BICM-OFDM system will be evaluated in terms of goodput-to-power ratio (GPR). Again, we remark here, that, even if this definition of EE is the same than that in [262], as pointed out, the goodput is here derived under a different scenario, i.e. BICM-OFDM links, and assumptions, i.e. practical modulation and coding schemes and ARQ mechanism, leading to a different and novel analytical expression of the metric of interest.

The design of distributed RA algorithms will be derived resorting to non-cooperative game theory [275], which is a branch of applied mathematics very popular in economics that has gained a lot of interest also in wireless communications. In fact, game theory offers an analytical framework that describes how rational entities interact and make appropriate choices so as to find their own maximum utility.

The main envisaged contributions, towards a HetNet able to (i) satisfy the strict QoS requirements of each user and (ii) account for the mutual interference between the macro-cell and the small-cells and between the small-cells themselves, can be summarized as follows.

- To study the properties of the proposed GPR objective function under specific QoS requirements in order to take into account demanding and content-rich applications.
- To solve the power allocation problem for GPR optimization for BICM-OFDM point-to-point communications under QoS constraints. This preliminary investigation, which is still an open issue in the literature, will constitute the basis for the analysis of the distributed and EE PA problem in SCNs.
- To study the distributed PA problem aimed at maximizing the GPR of each competitive user in the SC scenario described in the previous section. In this case, the mutual interference between users of different SCs and with the users of the macro-cell will be considered, as well as the heterogeneous QoS requirements of each SC user. The distributed PA problem will be addressed resorting to the non-cooperative game theory and issues related to the existence, uniqueness and efficiency of the solution will be investigated.

3.3.2.2 Adherence and relevance with the identified fundamental open issues

Distributed energy-efficient power optimization in cellular relay networks

As identified in the SoA analysis and the description in the previous section, the effort here, unlike solutions available in the literature, allows the multiple relays to cooperate in a distributed manner while satisfying power consumption constraints and quality-of-service requirements.

Distributed energy-efficient power optimization in heterogeneous networks

As follows from the SoA analysis a theoretical framework providing a systematic study of the relationship between the SE and the EE in a multipoint-to-multipoint interference channel is still missing. In particular, it is worth mentioning that the multi-user interference arising in parallel Gaussian multiple access channels can modify the fundamental trade-off between SE and EE as it is in point-to-point systems. As a consequence, in a heterogeneous scenario, where different users may decide to follow either the maximum SE or the maximum EE strategy, the behaviour of a single player may affect the trade-off between EE and SE across the entire network. This calls for a comprehensive model accommodating both the SE and the EE maximization problem under the same umbrella.

Distributed energy-efficient power optimization in BICM-OFDM systems

The activity will try to propose pragmatic design issues such as the use of practical modulation and coding schemes automatic repeat request (ARQ) mechanisms and packet-oriented transmissions.

3.3.2.3 Initial results

Distributed energy-efficient power optimization in cellular relay networks

For a fair comparison, the same total number of antennas is employed in the two different architectures. This means that, if we denote by N the number of receiving antennas for each relay in the scenario of Figure 3-16(a), the shared relay of Figure 3-16(b) will be equipped with $3N$ receiving antennas.

Let us focus, without loss of generality, on a given set of three adjacent clusters sharing the same subcarriers, and let us denote the total number of users simultaneously active over the same subcarriers within the three adjacent sectors by K. Clearly, K may take values within the set {1, 2, 3}. We denote by $\mathbf{h}_{r,i}$ the N-dimensional uplink channel vector whose entries $h_{r,i}(l)$ represent the channel gain from the transmit antenna at the ith UE to the l-th receive antenna of the r-th relay. The latter takes the form $\mathbf{h}_{r,i} = \mathbf{R}_r^{1/2}\mathbf{z}_i$ where $\mathbf{z}_i$ is a N-dimensional complex-valued vector whose entries are independent and identically distributed circularly symmetric complex Gaussian random variables with zero mean and unit variance, whereas $\mathbf{R}_r^{1/2}$ is a lower triangular matrix taken from the Cholesky decomposition of $\mathbf{R}_r$ that accounts for the spatial correlation at the relay side.

Denoting by $\mathbf{x}_r$ the vector collecting the samples received at the rth relay, we may write

$$\mathbf{x}_r = \sum_{i=1}^{K} \mathbf{h}_{r,i}\sqrt{p_i}\, d_i + \mathbf{w}_r \qquad (3.3.2.2)$$

where p_i is the transmit power of the ith UE and d_i denotes its data symbol, and $\mathbf{w}_r$ is the thermal noise that is modeled as a Gaussian vector with zero mean and covariance matrix $\sigma^2\mathbf{I}_N$ with $\mathbf{I}_N$ being the identity matrix of order N. To keep the complexity of the relay base station at a tolerable level, a simple linear detection scheme is employed for data detection. This means that the entries of $\mathbf{x}_r$ are linearly combined to form $y_k = \mathbf{g}_k^H\mathbf{x}_r$ where $\mathbf{g}_k$ is the vector employed for recovering the data of a generic user k. The SINR of user k takes the form

$$\gamma_k = \frac{p_k \left|\mathbf{g}_k^H \mathbf{h}_{r,k}\right|^2}{\left\|\mathbf{g}_k\right\|^2 \sigma^2 + \sum_{i=1,i\neq k}^{K} p_k \left|\mathbf{g}_k^H \mathbf{h}_{r,i}\right|^2} \quad (3.3.2.3)$$

from which its corresponding data rate r_k is computed as $r_k = \log\left(1+\gamma_k\right)$. When multiple relays are used, a maximum ratio combing (MRC) technique is employed. On the other hand, when a shared relay is employed, we resort to a minimum mean-square-error (MMSE) strategy, which requires knowledge of all channel vectors $\mathbf{h}_{r,i}$ for any $i \neq k$. This piece of information can be easily acquired by the shared relay using conventional estimation schemes that exploit the multiple antennas to separate the receiving signals.

A complete and accurate modeling of the system energy consumption is of primary importance when dealing with energy-efficiency since incomplete models might lead to wrong conclusions. Observe that, in addition to transmit power, UEs also incur in additional circuit power during transmission. While the transmit power models all the power used for reliable data transmission, we let the circuit power represent the average energy consumption of device electronics and it is independent of the transmission state. Denoting by $p_c^{(t)}$ the circuit power of the UEs, the overall power consumption $p_k^{(t)}$ of the kth UE is given by $p_k^{(t)} = 1/\eta p_k + p_c(t)$ with η accounting for the inefficiency of the power amplifier. In addition to this, the power expenditure at the relay $p_k^{(r)}$ for reliable data recovery has to be taken into account. The latter can be computed as $p_k^{(r)} = Np_c^{(r)}$, with $p_c^{(r)}$ being the circuit power of each antenna at the relays. From the above discussion, it follows that the total power expenditure $p_{T,k}$ required over the link to serve user k is given by

$$p_{T,k} = p_k^{(t)} + p_k^{(r)} = \frac{1}{\eta} p_k + p_c(t) + \frac{N}{M} p_c^{(r)} \quad (3.3.2.4)$$

where M is the number of served users, which equals $M = 1$ in the case of distributed relays, and $M = K$ when the relay is shared across different cells. The energy efficiency of the link can be thus computed as

$$u_k = \frac{r_k}{p_{T,k}} \quad (3.3.2.5)$$

To proceed further, we observe that in cellular networks UEs are usually required to satisfy data requirements given by $r_k \geq \rho_k$ where ρ_k are quality-of-service constraints in terms of minimum data rate to be achieved.

Based on the above formulation, we have then formalized the optimization problems for the operating scenarios depicted in Figure 3-16. In particular, when a shared relay is employed, the optimization problem has been formulated as

$$\begin{aligned} \mathbf{p}^* = \quad & \arg\max_{\mathbf{p}} \quad \sum_{k=1}^{K} u_k \\ \text{subject to} \quad & p_k^{(\min)} \leq p_k \leq p_k^{(\max)} \quad \forall k \\ & r_k \geq \rho_k \quad \forall k \end{aligned} \quad (3.3.2.6)$$

where $\mathbf{p} = [p_1,p_2,\ldots,p_K]^T$ whereas $p_k^{(\min)}$ and $p_k^{(\max)}$ denotes respectively the minimum and maximum transmit power at transmitter k. To the best of our knowledge, the solution of the above problem is hard to find and not known yet.

When multiple relays are used the problem in Figure 3-16 cannot be solved in a centralized fashion by each relay, as the channel of interfering users is not locally available. This means that each ST must solve the above problem in a decentralized way in order to compute its optimal p_k^*. This amounts to solving the following problem

$$\begin{aligned} p_k^* = \quad & \arg\max_{p_k} \quad u_k \qquad\qquad \forall k \\ & \text{subject to} \quad p_k^{(\min)} \le p_k \le p_k^{(\max)}, \\ & \qquad\qquad\quad r_k \ge \rho_k . \end{aligned} \tag{3.3.2.7}$$

The above problem has been restated as a non-cooperative game with complete information and its solution will be investigated using the tools of game theory.

The roadmap for the above research activity is to:

- Perform a state-of-the-art analysis to identify possible similar approaches in the literature, that can be useful for a fair comparison with current solutions available in the literature;
- Perform in better detail the problem formulation, possibly looking for alternative models and/or assumptions;
- Derive closed-form expressions for the solution of the optimization problems, also including the derivation of necessary and/or sufficient conditions for the existence and the uniqueness of such resource allocations;
- Identify adequate parameters for circuit power and fixed power expenditure for different receiver structure, that better model the electrical section of the devices under investigation;
- Include realistic models to mimic imperfect channel state information and correlation between spatial antennas;
- Model the UE distribution across the space domain, so as to provide simulations that are able to quantify the impact of the proposed solutions on a macro-cellular scenario.

Distributed energy-efficient power optimization in heterogeneous networks

The major results that have been obtained within this activity so far can be found in [291] and are summarized in the next. In particular, in [291] the energy-efficient maximization problem has been reformulated as a rate maximization Nash equilibrium problem in which the strategy sets of the players are coupled among each other. This is achieved by first reformulating the problem as the solution of a classical fixed-point problem and then using the quasi-variational inequality theory. To see how this comes about, denote by $t_k^*(\mathbf{p}_{-k})$ the optimum value of t_k within the feasible set of the problem below for a given $\mathbf{p}_{-k}$ [291]

$$\begin{aligned} \max_{\mathbf{y}_k, t_k} \quad & R_k(\mathbf{y}_k / t_k, \mathbf{p}_{-k}) \qquad \forall k \\ \text{subject to} \quad & t_k(\mathbf{1}^T \mathbf{y}_k / t_k - P_k) \le 0 \\ & t_k(\psi_k + \mathbf{1}^T \mathbf{y}_k / t_k) \le 1 \end{aligned} \tag{3.3.2.8}$$

Then, the following result follows [291].

Proposition 2: Let $g_k(\mathbf{p}_k, \mathbf{p}_{-k})$ be

$$g_k(\mathbf{p}_k, \mathbf{p}_{-k}) = \psi_k + \mathbf{1}^T \mathbf{p}_k - \frac{1}{t_k^*(\mathbf{p}_{-k})} . \tag{3.3.2.9}$$

Then, the best response $b_k(\mathbf{p}_{-k})$ of player k can be computed as

$$\mathbf{p}_k^* = \Pi_{\bar{Q}_k(\mathbf{p}_{-k})}\left(-\xi_k - \sum_{i \ne k} \mathbf{D}_{k,i} \mathbf{p}_i \right) . \tag{3.3.2.10}$$

In addition to this, the following result can also be proven [291].

Proposition 3: Let

$$Q(\mathbf{p}) = \prod_{k=1}^{K} Q_k(\mathbf{p}_k) \tag{3.3.2.11}$$

where $Q_k : P_{-k} \to 2^{P_k} \ \forall k$ are the set-valued functions

$$Q_k(\mathbf{p}_{-k}) = P_k \cap \left\{ \mathbf{p}_k \in \Re_+^N : g_k(\mathbf{p}_k, \mathbf{p}_{-k}) \le 0 \right\} \ , \tag{3.3.2.12}$$

and 2^{P_k} is the power set collecting all the above possible subsets of P_k. A power allocation profile $\mathbf{p}^*$ is a Nash equilibrium of the energy efficient maximization problem if and only if it solves the QVI(Q,**F**), where $\mathbf{F}(\mathbf{p}) = \left\{ \mathbf{F}_k(\mathbf{p}) \right\}_{k=1}^{K}$ are the mappings.

Stated formally, $\mathbf{p}^*$ is such that:

$$\left(\mathbf{p} - \mathbf{p}^* \right)^T \mathbf{F}\left(\mathbf{p}^* \right) \ge 0 \quad \forall \mathbf{p} \in Q(\mathbf{p}^*) \, . \tag{3.3.2.13}$$

A close inspection of QVI(Q,**F**) reveals that the set of Nash equilibria of G_E is not simply defined by the maximum available transmit power as in G_R but it depends on the other players strategies through $Q(\mathbf{p})$. The existence and uniqueness of the generalized Nash equilibria of G_E have been studied in [291]. This is accomplished exploiting the Karush-Khun-Tucker (KKT) conditions of the individual maximization problems of QVI(Q,**F**) and the sequentially bounded constraint qualification (SBCQ).

Capitalizing on the interpretation of the player's best-response as a Euclidean projection, a graphical comparison between the SE and EE best responses is provided in Figure 3-17 for a 2-subchannel case. In particular, Figure 3-17 shows the player k's best response to two different strategies of the other players. It is worth observing that the hyperplane below the trade-off region depends on the other players' strategies and that every strategy providing a given trade-off between the maximum SE and the maximum EE must lie on the grey zone between two hyperplanes. In addition to this, the following result can also be proven [291].

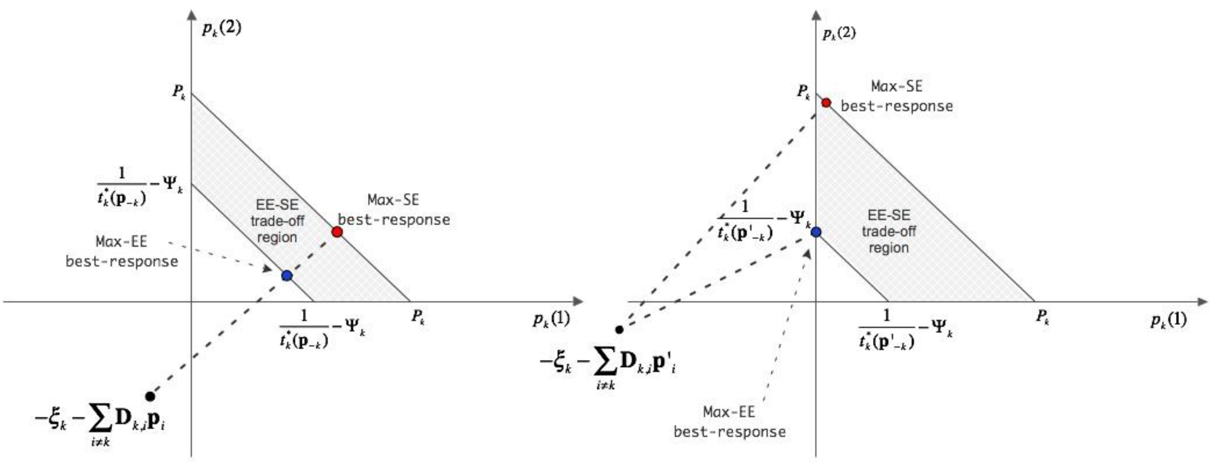

Figure 3-17 : Graphical interpretation

The existence and uniqueness of the generalized Nash equilibria of G_E have been studied in [291]. This is accomplished exploiting the Karush-Khun-Tucker (KKT) conditions of the individual maximization problems of QVI(Q,**F**) and the sequentially bounded constraint qualification (SBCQ).

A procedure to numerically find the generalized Nash equilibrium is also given in [291]. Roughly speaking, the key idea is to achieve the equilibrium by solving a properly defined sequence of penalized VIs whose mappings are decreased by a properly defined penalty term [293].

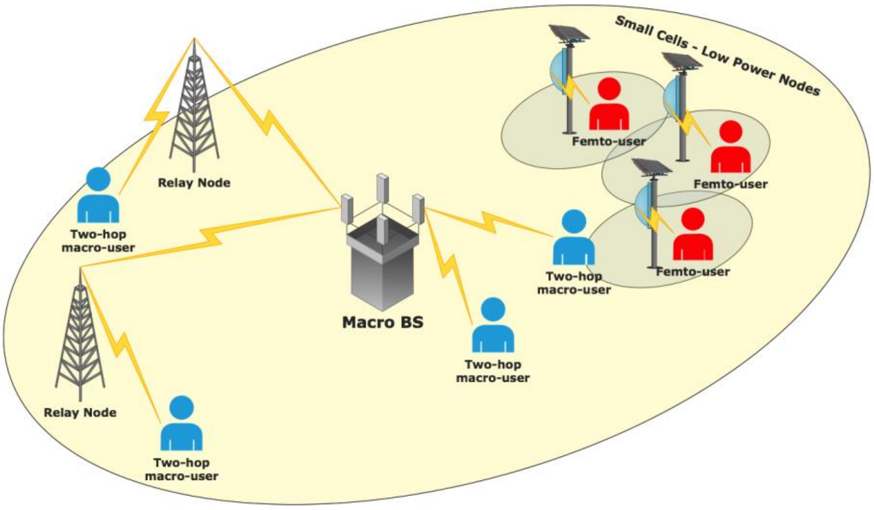

Figure 3-18: Two-tier heterogeneous network.

On the basis of the above results, further research activities will be done to extend the above framework to a more general network as the one depicted in Figure 3-18, wherein multiple small-cells are deployed inside a macro-cell coverage region, thus sharing the same frequency resource [273]. Small-cell networks are particularly useful to serve low-mobility users closely located to an access-point [273]. The main advantage in using this layered architecture stems from the superior signal reception due to the short distance between transmitter and receiver. As a consequence, the small-cell users can transmit with low power levels, thereby prolonging battery life. At the same time, the signals transmitted by the macro-cell users, or macro-users for short, might cover long distance to reach the receiver located at the macro-base station. Hence, in order to enhance the battery life of the macro-users, relay-assisted transmissions are envisaged for those users located near the cell edge. Furthermore, according to the incumbent need of greening network infrastructures, relay nodes might be capable of guaranteeing minimum rate requirements at the source nodes while transmitting in an energy-efficient manner. In the heterogeneous scenario depicted in Figure 3-18, it would be extremely difficult to achieve coordination among the various nodes belonging to different cells and using different network infrastructures. Resorting to the framework depicted in this section, we aim at showing that the competitive power control problem for the outlined two-tier wireless network is an instance of the generalized Nash equilibrium described above. Then, a distributed power control algorithm could be derived resorting to the quasi-variational inequality theory [293]. This is an interesting on-going research activity that wills likely lead to interesting outcomes.

The roadmap for the above research activity is to:

- Perform a state-of-the-art analysis to identify possible similar approaches and to look for alternative models and/or assumptions;
- Identify adequate parameters for circuit power and fixed power expenditure for different receiver structure, that better model the electrical section of the devices under investigation;
- Include realistic models to mimic heterogeneous networks;
- Find a good way to evaluate the trade-off between the rate and energy-efficient maximization conflicting requirements for heterogeneous networks.

Distributed energy-efficient power optimization in BICM-OFDM systems

The proposed research activity has first produced an in-depth analysis of the state-of-the-art of energy efficient communications, as reported in the previous section. The activity is now focusing on the definition of the operating scenario, identifying the main open issues and tools that could properly support the analysis of the problem. In particular, in the analysis of the GPR optimization problem, we can take advantage of the results we obtained in two preliminary works to this activity done within this project: [294], [295]. In the former, the PA problem for goodput maximization in point-to-point BICM-OFDM link has been addressed and solved resorting to the quasi-variational inequality (QVI) theory. In the latter, a distributed PA algorithm for PSR maximization in multi-point to multi-point BICM-OFDM links has been solved by modeling the problem as a non-cooperative game and exploiting the contraction mapping theory to design the distributed PA algorithm.

3.3.2.4 Achievements and planned activities

The research work in this activity is segregated into three sub-topics.

- JRA 1.3.3.B.1 Distributed energy-efficient power optimization in cellular relay networks

- JRA 1.3.3.B.2 Distributed energy-efficient power optimization in heterogeneous networks

- JRA 1.3.3.B.3 Distributed energy-efficient power optimization in BICM-OFDM systems

All the three topics are being carried out in the framework of Newcom#, starting from February 2013, and are reported in the present deliverable. The sections in the deliverable, associated with the specific descriptions of the JRAs 1.3.3.B.1 and 1.3.3.B.2, and so the contributions to the corresponding state of the art sections, have been written and edited by Luca Sanguinetti, Giacomo Bacci (CNIT-Pisa) and Veronica Belmega (CNRS-ENSEA) for JRA 1.3.3.B.1 and by Luca Sanguinetti, Giacomo Bacci (CNIT-Pisa) and Ivan Stupia (UCL) for JRA 1.3.3.B.2. Riccardo Andreotti (CNIT-Pisa) contributed to the state of the art description and problem formulation of JRA 1.3.3.B.3. The state of the art sections 2.3.2.1 and 2.3.2.2 in D13.1 of JRAs 1.3.3.B.1 and 1.3.3.B.2, respectively, has been written and edited by Luca Sanguinetti (CNIT-Pisa). Giacomo Bacci (CNIT-Pisa), Veronica Belmega (CNRS-ENSEA) and Ivan Stupia (UCL) actively participated in the search of the key papers, which have set the basis of the collaboration and have allowed to clearly identify the most interesting open research challenges. The latter have been first briefly summarized in section 2.3.2.4 and then extended in 3.3.2. The section 2.3.2.3 of the state of the art of JRA 1.3.3.B.3 has been edited by Riccardo Andreotti and Paolo Del Fiorentino (CNIT-Pisa). This survey on energy efficient communications and game theoretical approaches for distributed resource allocation problems helped in identifying open issues and topic of interest for the development of the JRA.

In the topic of “Distributed energy-efficient power optimization in cellular relay networks” the research activity has been done by Luca Sanguinetti and Giacomo Bacci (CNIT-Pisa) and Veronica Belmega (CNRS-ENSEA). A joint paper, entitled “Distributed energy-efficient power optimization in cellular relay networks with minimum rate constraints”, done by the above mentioned partners will be presented at ICASSP 2014, Florence, Italy. In this work, a distributed power control algorithm is proposed for energy-efficient uplink transmissions in interference-limited multicellular networks, equipped with either multiple or shared relays. The proposed solution is derived by modeling the mobile terminals as utility-driven rational agents that engage in a non-cooperative game, under minimum-rate constraints. The theoretical analysis of the game equilibrium is used to compare the performance of the two different cellular architectures. Extensive simulations show that the shared relay concept outperforms the distributed one in terms of energy efficiency in most network configurations.

In the topic of “Distributed energy-efficient power optimization in heterogeneous networks” the research activity has been done by Luca Sanguinetti and Giacomo Bacci (CNIT-Pisa) and Ivan Stupia and Luc Vandendorpe (UCL). A joint paper, entitled “Energy-Efficient Power Optimization in Heterogeneous Networks: A Quasi-Variational Inequality Approach”, done by the above mentioned partners has been submitted to IEEE Transactions on Signal Processing for a possible publication as a full journal paper. This work starts dealing with the power allocation problem in a multipoint-to-multipoint network in which the transmit and receiver pairs are modeled as rational players that engage in a non-cooperative game in which each one aims at selfishly maximizing its own energy efficiency. This game is first reformulated as a generalized Nash equilibrium (GNE) problem in which players aim at maximizing their own rates while satisfying coupling constraints and it is then solved using the advanced theory of quasi variational inequality (QVI). The above results are eventually extended to a more general and heterogeneous framework in which each player may indifferently follow a rate or an energy-efficient maximization strategy. The equivalence between the GNE problem and the QVI provides with all the mathematical tools to study the existence and uniqueness of the GNE points of such a heterogeneous game and to derive an alternative algorithm based on the sequential penalty approach that allows the network to converge to its GNE in a distributed manner.

In the topic of “Distributed energy-efficient power optimization in BICM-OFDM systems” the research activity has been done by Riccardo Andreotti, Paolo Del Fiorentino, Vincenzo Lottici and Filippo Giannetti (CNIT-Pisa) in collaboration with Fabio Martignon and Lin Chen (CNRS-LRI). A joint paper, entitled “Distributed power allocation based on PER minimization for non-cooperative multicarrier systems under interference constraints”, done by the above mentioned partners was submitted to ICASSP 2014, Florence, Italy. The paper proposes a distributed power allocation (PA) strategy aimed at minimizing the packet error rate (PER) of secondary (or, small cells) users with the constraint of keeping the interference to the primary receiver (or, macro base station) under a given threshold. The proposed PA is formulated as a non-cooperative game, relaxed by applying a pricing mechanism and finally, iteratively solved by exploiting the contraction mapping theory. Numerical simulations confirm the convergence and the effectiveness of the proposed algorithm.

The research activity within JRA 1.3.3.B.2 was presented during an informal meeting with people from Alcatel-Lucent in Paris (France). The participants were quite interested on how a game-theoretic formulation of the power allocation problem in heterogeneous networks may be used to derive an iterative and distributed solution easy to be implemented with only a small exchange of information. Moreover, during the second year, the JRA 1.3.3.B.2 will be involved in a Newcom# dissemination event that will be held in Istanbul on April 4, 2014 at AVEA Laboratories.

So far, all the above JRAs have not established significant relations with Track 2 activities since the first year has been mainly dedicated to the mathematical formulation and analysis of the problem under investigations. However, during the NEWCOM# Track 1-2 meeting on "the Future of Wireless Communications" that was held in Lisbon the 21st of January 2014, Luca Sanguinetti, Giacomo Bacci (CNIT-Pisa) and Ivan Stupia (UCL) have received interesting inputs in regards to JRA 1.3.3.B.2 from CTTC affiliates (that are largely involved in Track 2 activities). As an action plan for the future, Luca Sanguinetti and Ivan Stupia will visit CTTC for a few days in April. This visit will first give them the possibility to better explain and discuss the main results of JRA 1.3.3.B.2 to CTTC affiliates and then will provide them an excellent opportunity to discuss and formulate future joint activities within Track 2.

The planned activities are described below for each topic.

<u>JRA 1.3.3.B.1 Distributed energy-efficient power optimization in cellular relay networks</u>

The activity of this JRA during the second year will be focused on using the results obtained during the first year to derive a distributed resource allocation (power and subcarriers) scheme for the uplink of an OFDMA-based small-cell network, in which the mobile terminals are modeled as utility-driven rational agents that aim at maximizing the number of bits correctly delivered at destination per unit of energy consumed, under minimum-rate constraints. The activity will be jointly carried out by Luca Sanguinetti, Giacomo Bacci (CNIT-

Pisa) and Veronica Belmega (CNRS-ENSEA) and will be first focused on extending the game-theoretical formulation to the new problem under investigation taking into account that small-cells are characterized by low-power and have low-computational capabilities. The goal will be that of allocating the resources (power and subcarriers) across the network in a scalable and adaptive manner, while improving the performance of each user in terms of energy efficiency compared to the alternative solutions that have been individuated during the first year. The research activity will also involve Panayotis Mertikopoulos (CNRS) whose expertise in game theory will be very useful to study and analyze the Nash equilibrium points of the game.

JRA 1.3.3.B.2 Distributed energy-efficient power optimization in heterogeneous networks

Concerning JRA 1.3.3.B.2, the action plan for the second year is to extend the research activity to a two-tier small-cell network. The latter is a promising solution to reduce energy consumption in cellular networks and it is basically founded on the idea of a very dense and heterogeneous deployment of operator-installed low-cost and low-power base stations. Small-cell networks are particularly useful to serve low-mobility users closely located to an access-point. The main advantage in using this layered architecture stems from the superior signal reception due to the short distance between transmitter and receiver. As a consequence, the small-cell users can transmit with low power levels, prolonging battery life. In this context, relay nodes are used by the macro-cellular network to reduce the transmit power of the (so called) macro users that are located near the cell edge. According to the incumbent need of greening network infrastructures, relay nodes might be capable of guaranteeing minimum rate requirements at the source nodes while transmitting in an energy-efficient manner. In such a scenario, the development of centralized power control algorithms would be extremely challenging, as it would require the coordination among all the above heterogeneous entities. The goal for the second year will be that of formalizing the power optimization problem in such networks as a generalized Nash equilibrium problem and of computing its solution may in a distributed manner using the sequential penalty approach developed during the first year. All partners will jointly carry out this activity. In particular, Luca Sanguinetti, Giacomo Bacci (CNIT-Pisa) will be mainly involved in the problem formulation and analysis of the Nash equilibrium points whereas the activity of Ivan Stupia and Luc Vandendorpe (UCL) will be mainly focused on studying the converge properties and conditions of iterative solutions.

JRA 1.3.3.B.3 Distributed energy-efficient power optimization in BICM-OFDM systems

Concerning JRA 1.3.3.B.3, the action plan for the second year starts from the results obtained during the first year of the activity. Here, the main result obtained was the solution of the goodput constrained energy efficient (EE) power allocation (PA) problem for a point-to-point case, i.e., one transmitter and one receiver, without interference. This preliminary investigation, which was still an open issue in the literature, constituted the basis for the analysis of the distributed and EE PA problem in small cell networks. This problem was formulated as a non-cooperative game and the solution was found based upon the best response. Starting from these outcomes, the first issues to be addressed in the second year of the activity are the investigation of the existence and uniqueness of the solution of the distributed PA problem. Then, analysis of the efficiency of the solution and its improvement via a pricing mechanism is envisioned. Finally, since the main limiting factor of the performance is represented by the multi-user interference, interference cancelation techniques could be taken into account, leading to an alternative formulation of the game, for instance such as a Stackelberg game. In this case, analysis of the features of the new game and of the trade-off between efficiency of the solution and quantity of required information, compared to the game based on the Nash equilibrium, is needed. The investigation on these aspects is envisioned for the second half of the second year and the third year.

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

Leader: Danilo Abrignani (CNIT-UniBO)
Main partners: Danilo Abrignani and Roberto Verdone (CNIT-UniBO), Lorenza Giupponi (CTTC)

3.3.3.1 Description

One major characteristic of M2M communications is that there are multiple Machine Type Communication (MTC) servers, which operate an enormous number of MTC devices (e.g. meters operated by the power plant in the smart grid). As a result, how to build connections from each MTC server to a large number of MTC devices emerges as a critical issue. In 3GPP it is proposed that each MTC device attaches to the existing cellular infrastructure through which access to the core is provided. Herein, the considered architecture includes M2M devices connected directly or via M2M gateways to the evolved UTRAN (E-UTRAN) architecture, together with traditional human to human (H2H) User equipments (UEs). The eNBs in E-UTRAN are connected to the evolved packet core (EPC) via serving gateways (S-GW). The Packet data network gateway (P-GW) acts as the gateway to the core network and provides connectivity to the IP backbone. The IP backbone provides connectivity among M2M devices, UEs, servers and users. The Evolved Packet System (EPS) including E-UTRAN and EPC form the M2M and the cellular access network. In LTE-A, besides getting access to E-UTRAN through an eNB, machines can also get access through small cells, such as a relay node or a Home eNB. Relay nodes are connected to the EPC via the Donor eNB, while HeNBs are directly connected to the S-GW, or through a H2NB gateway. The joint M2M and H2H architecture is shown in Figure 3-19.

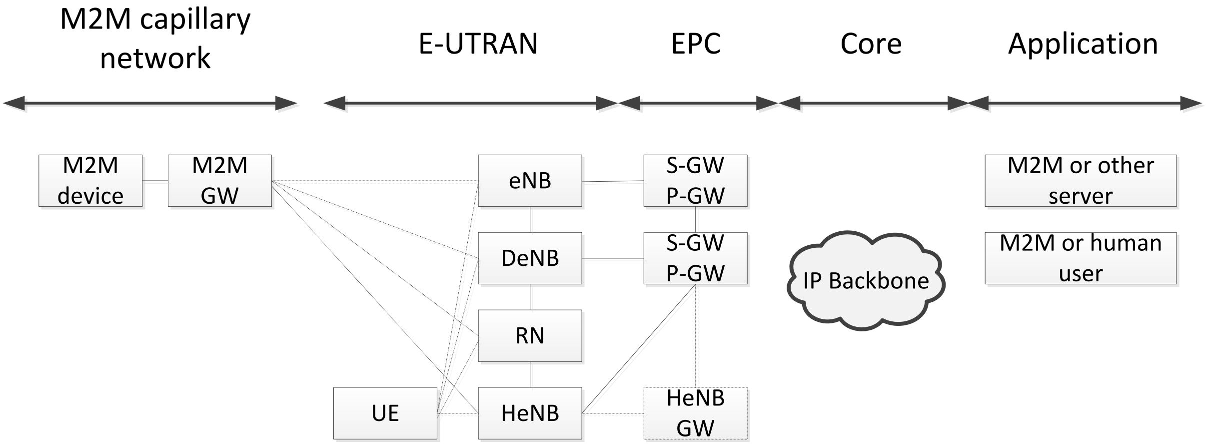

Figure 3-19: M2M and H2H system architecture

The scenario considered in this JRA is an urban scenario in a near future smart city, with the focus on a big street supported by a dense small cell deployment, able to support both H2H and M2M traffic. The high level scenario is depicted in Figure 3-20, where the dense small cell deployment is co-located with the lamp posts of the street. The same lamp posts are also characterized by the presence of a metropolitan wireless sensor network (MWSN) on them, which collects information and provides services using low-complexity and low-cost devices in Internet of Things (IoT) applications.

The M2M traffic generated by the MWSN has some peculiarities: in IoT context the 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; furthermore different applications have different requirements in terms of throughput, maximum tolerable packet loss rate, maximum delay, etc. which in addition, is influenced by the information lifetime. The aggregated M2M and H2H traffic collected by the small cells can be collected by a LTE gateway and then either routed to an eNB (LTE macrocell) and then to an EPC, if the small cells are relay nodes, or directly to the EPC if these small cells have HeNB or picocells functionalities.

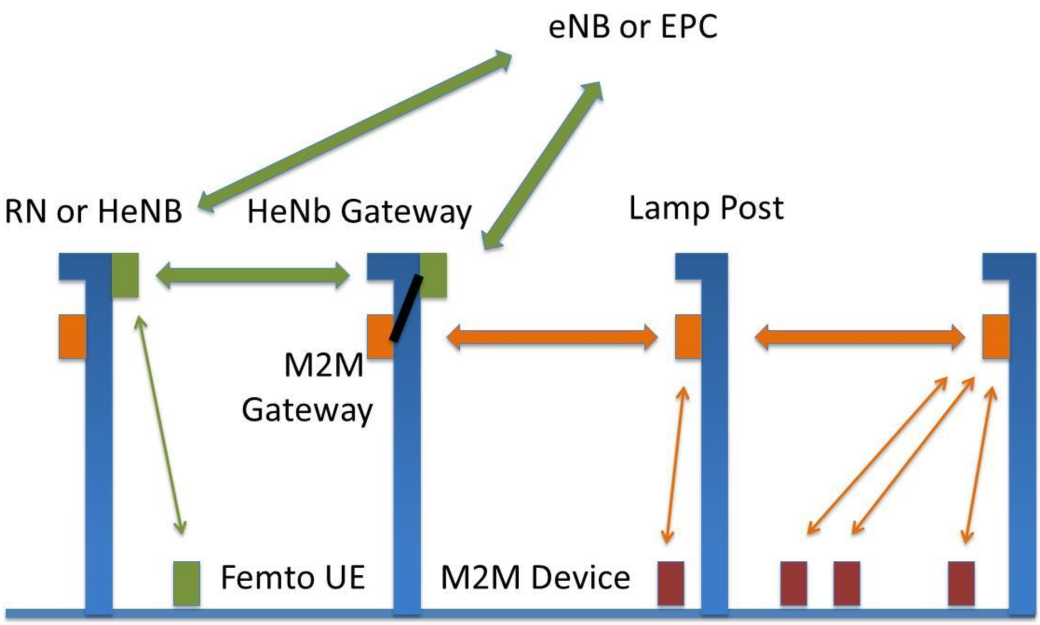

Figure 3-20: High level scenario

The small cells could be deployed by the network operator, or by the provider of smart city solutions. In the first place, we will focus on a network operator deploying the LTE small cells in licensed bands. The challenge is in the joint scheduling in this band of the M2M traffic, as well as of the human generated traffic. On the one hand, we have to design the scheduler to deal with an intensively deployed small cell network, where coexistence problems arise in terms of inter-cell interference. The scheduler will have to take into account the different kinds of traffic, characterized by different requirements which can be served by this kind of network, i.e. M2M and H2H scheduling of the resource between all the users in a single small cell to maximize the number of users served and the throughput.

3.3.3.2 Adherence and relevance with the identified fundamental open issues

In section 2.3.7.3 the main challenges, related to using the 3GPP cellular infrastructure as a communication support for M2M traffic, were analyzed. In this JRA the plan is to design a traffic feature-aware scheduler inside the small cell to efficiently manage the coexistence between M2M and H2H traffic and thus addressing one of the fundamental issues.

3.3.3.3 Initial results

The joint research activity has still not produced any tangible result. Currently the activities are focusing on setting up the scenario and defining meaningful M2M traffic to be scheduled in the proposed scenario. As already mentioned M2M traffic is different compared to human generated traffic. Generally, the amount of data that is necessary to transmit is very low and infrequent, so that cellular networks are not designed to transmit this information efficiently. The plan in this activity is to design a traffic feature-aware scheduler inside the small cell to efficiently manage the coexistence between M2M and H2H traffic, by keeping in mind to incorporate in this design the need for self-organizing capabilities, which are already part of LTE since release 8. The scheduler aims at maximizing the throughput while at the same time guaranteeing inter-cell interference coordination in the dense deployed proposed scenario.

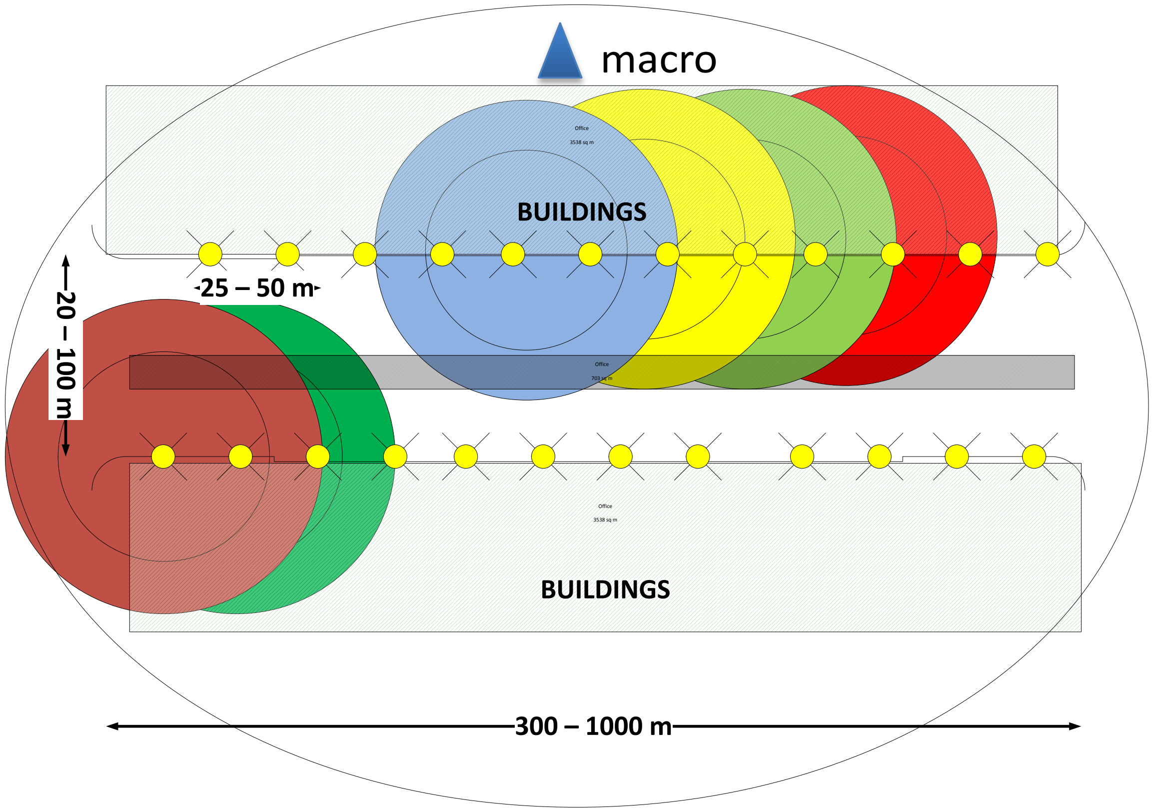

Figure 3-21: Simulation scenario

To carry out this work, the partners will take advantage of the LTE simulator LENA (http://iptechwiki.cttc.es/LTE-EPC_Network_Simulator_(LENA)), based on Network Simulator v.3 (ns-3 http://www.nsnam.org/), developed at CTTC. Through this tool, the partners have already deployed the scenario shown in Figure 3-21. 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. The small cells are deployed on each lamp post or on each two lamp post. Generally the lamp posts on the same side of the street are 25 through 50 meters. Lamp posts are from 6 to 9 meters on top of the street while the road is large from 20 to 100 meters.

A great amount of work in this phase has been devoted to the definition and implementation in ns-3 of different M2M traffic models with different QoS requirements. Contributions in literature on traffic models for MTC are still little. Among them, we highlight the advancements achieved in the context of the FP7 Lola Project in [315], where different M2M applications are analysed to found a model that generally describes the M2M traffic. 3GPP also has some work on the classification and modelling of M2M traffic, in 3GPP TSG RAN WG1 [316], [317]. Additional work can also be found in [318].The adopted model herein is based on Markov Chains and on a general On-Off model with different distribution for the packet sizes and inter-arrival times of packets (LogNormal, Gaussian, Weibull, Constant size).

3.3.3.4 Achievements and planned activities

All the work that is being carried out and reported in this deliverable has been realized uniquely in the framework of Newcom#, starting from May 2013. During the first months of the activity, the partners have been engaged in the definition of the joint Smart-city and small cell scenario, the implementation of it in a LTE release 10 compliant network simulator and in the definition of the research problem and algorithmic solution for it. Danilo Abrignani (CNIT-UniBO) spent one month in Barcelona, CTTC, hosted by Lorenza Giupponi (CTTC). They have both been involved in the scenario definition, together with Roberto Verdone (CNIT-

UniBO). The network simulator in use has been implemented by CTTC and it is open-sourced, Danilo Abrignani is taking care of the implementation. The algorithmic solutions are being designed by the joint work of CTTC and CNIT-UniBo.

The section in the deliverable, associated with the specific description of the JRA, and the state of the art section, have been written and edited by Lorenza Giupponi. Danilo Abrignani contributed to the scenario and problem definition, and to the initial results section. The work on the state of the art section has been written and edited by Lorenza Giupponi. The study of the literature that the two partners have developed jointly has been key for the definition of the interesting challenges that have been reported in the deliverable and are being addressed in the context of the JRA. The partners have clearly identified the most interesting open research challenges, as described in section 2.3.7, and then have decided to focus on the resource allocation and scheduling problem and on the need for improvement in spectrum utilization, since these aspects were particularly interesting for the both the M2M and the small cell scenarios.

The research activity was presented during an informal meeting with an Italian large company, SIAE Microelettronica, which is leader in backhaul wireless solutions for cellular systems. The company was quite interested in our activity, in fact they proposed to prepare a joint proposal for upcoming H2020 call that will take into account our scenario. Moreover, during the second year this JRA will be involved in some Newcom# dissemination events with industries in Europe.

Related to Track 2 activities, some interesting input for this JRA may come from the JRA6 in WP2.2. Basically this JRA deals with IoT scenario and it aims to evaluate different paradigms and standards for M2M application in wireless sensor networks. From this work it is possible to derive some real data from M2M application; those are useful to validate traffic models that will be implemented in the scenario of this JRA. Moreover, detailes on quality requirements and overhead of different application and standard can be derived.

During the second year of the project, the plan to start obtaining the first results to be published. Early 2014, we have presented our work in a COST IC1004 meeting. The work deals with the evaluation of M2M scheduling opportunities in a LTE small cell network for Smart city applications. Here, we face the challenge of scheduling M2M traffic over a LTE small cell network densely deployed over the lamp posts of a big boulevard for smart city applications. We present the 3GPP architecture which supports the proposed scenario and discuss the main open research challenges together with the relevant state of the art. We also focus on the scheduling of M2M traffic in the uplink of this scenario characterized by high inter-cell interference. We evaluate in this context, with the support of a LTE Release 10 compliant network simulator, the scheduling opportunities taking into account the transmission constraints imposed by the LTE Single Carrier Frequency Division Multiple Access (SC-FDMA) uplink access method. Simulation results 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 network. We plan to extend this work and submit it to European Conference on Networks and Communications.

We are also working towards an algorithmic solution for scheduling with interference constraints in this scenario, which will be submitted with numerical and system level results to one or two big conferences before spring, e.g. VTC, PIMRC or Globecom 2014. Danilo Abrignani is taking care of the algorithmic details of the solution and of the implementation for numerical and system level results. Lorenza Giupponi is supervising the activity together with Roberto Verdone (CNIT/UniBo).

During the rest of the second year, we plan to enrich our results with realistic traffic models and submit the work for magazine and journal publication. Also we will compare our approach with alternative numerical solutions, optimal and suboptimal. We are currently working on the uplink design, and we will extend the work also for downlink M2M applications.

Finally, during the third year, we plan on including in the interference and scheduling problem, not only the access link, but also the backhaul one. This will hopefully allow us to work in cooperation with an important Italian Company, provider of backhaul solutions, with whom we are currently collaborating for a joint proposal submission in next European Project call 1.

4.Conclusions

Research on energy- and bandwidth-efficient communications and networking is quite extensive nowadays and encompasses many and important research topics. Out of the plethora of such topics, this WP has chosen to focus on those specific areas and research problems in which the partners have already demonstrated experience and knowledge, thus allowing them to effectively collaborate and thus enhance their common research activities and agendas, which is one of the objectives of this Network of Excellence. In order to support the said cooperation between the partners and to minimize overlap between the various research efforts, a specific research-harmonization procedure has been adopted and which has resulted in the down-selection of the 9 JRAs presented in this Deliverable.

In the first year of the project, all these JRAs have initiated their joint research work; this Deliverable provides the associated roadmap for this beginning. Based on the analysis of the State of the Art and the identification of the underlying fundamental research issues, each JRA activity has documented its adherence and relevance to these open research issues by highlighting the added value of the expected results. As it is shown in this Deliverable, depending on the current maturity of the collaborations, some JRAs have already produced results that are presented or submitted in scientific journals, conferences and workshops. It is expected that the dissemination activities will accelerate in the second year of the project for all included JRAs.

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