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State-of-the-Art on scheduling techniques and design paradigms, and intended contribution

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Editor(s), (names and affiliations): Virginia Corvino (CNIT)
Participating institutions: CNIT, NKUA/IASA, CNRS, UPC, CTTC, LNT/TUM, UCL
Contributors (names): Virginia Corvino, Giulio Dainelli, Marco Moretti, Velio Tralli, Roberto Verdone, Nikos Dimitriou, David Gesbert, Ana Pérez-Neira, Lorenza Giupponi, Danail Traskov, Felix Brah
Internal Reviewer(s) (names and affiliations): Sergio Benedetto (ISMB), Roberto Verdone (CNIT), Danail Traskov (LNT-TUM), Felix Brah (UCL)
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Abstract: This deliverable reports on the achievements after the first six months of WPR.8, whose aim is the investigation of scheduling and adaptive radio resource assignment techniques, and the determination of new algorithms, through the use of the most innovative and promising design tools and methods.

The WP is organized in three Tasks, dealing with the following subtopics:
1 – Multi-Carrier and/or Space Division based air interfaces, like those exploiting OFDMA and/or MIMO techniques, widely used in current and future standardized wireless systems;
2 – distributed wireless networks, where the lack of a centralized control poses problems to radio resource assignment procedures;
3 – systems characterized by different heterogeneous air interfaces that can interact.

During the first six months, the state of the art on the topic and the plan for scientific activities within the WP have been defined. They are reported in Sections 2 and 4 – 5, respectively. The state of the art has been summarized based on consideration of about one hundred forty references, selected through a bottom – up procedure by each participant partner. The five Joint Research Activities (JRAs) defined within the WP and described in this Deliverable, involve all partners and focus on specific aspects within the three Tasks. Therefore, as promised by its title, this Deliverable reports the state of the art, and the intended contributions of WPR.8, during the NoE life.

However, much more is contained in this Deliverable. Section 1, while introducing the general objectives of the WP, also provides definitions which will represent the common basis for all activities planned within the WP: terms generally used in the literature, such as “scheduling” as opposed to “radio resource assignment”, “radio resource” or “radio resource unit”, are defined. The JRAs performed within the WP will then share a common language. Moreover, Section 3 represents the fundamental result after the first six months: the many algorithms and approaches used in the literature and summarized in Section 2, are then re-considered in Section 3 under the viewpoint of the design method. The scope here is the identification of the basic properties of the most performing algorithms, and of their design principles; the usefulness of this effort stands in the identification of the basic features that the designer of scheduling and radio resource assignment algorithms should have in mind, when proposing new techniques. Therefore, Section 3 is the core part of this document.

The Deliverable then ends in Section 5 by committing towards some results and a schedule of planned activities.

Finally, the activities within this WP will be performed by the following partners: CNIT, NKUA/IASA, CNRS, UPC, CTTC, LNT-TUM, UCL. In particular, the editor of the Deliverable is from CNIT, whereas the sub-editors are the Task leaders, coming from CNIT, NKUA/IASA and UPC.

Keyword list: resource allocation, scheduling, multi-carrier and space division systems, distributed networks, cognitive radio, heterogeneous networks.

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1. INTRODUCTION

With the advent of 3rd Generation (3G) mobile radio systems, scheduling has been gaining more and more interest among researchers involved in wireless networks. In fact, wireless systems until 2nd Generation (2G) were characterized by hard capacity (*i.e.*, a deterministic number of users can be served by a given base station) and only vocal application was supported, meaning that link requirements to be met were only set in terms of block error rate and delay. So, in such kind of system the planning phase was of primary concern. From 3G on, wireless systems have been characterized by a plethora of multimedia applications available to the end user, raising the problem of how to efficiently manage the many degrees of freedom offered by the system. In fact, each application type is characterized by specific requirements, which can be set in terms of average bit rate, maximum Bit Error Rate (BER) and, hence, minimum Signal-to-Interference-plus-Noise Ratio (SINR), maximum delay, et cetera. All these features are usually considered as part of a set of characteristics summarized under the expression "Quality of Service" (QoS), which could be defined as *the set of requirements to be met by the system for a specific application requested by a user*. Due to the application differentiation, also QoS should be handled in a differentiated way. Moreover, the offered traffic continuously changes according to the number of users and the specific mix of applications required, since each user can request different applications. So, in such a situation, QoS cannot be achieved through a planning procedure, which statically configures the system, but it is dynamically pursued by a set of functionalities grouped under the term "Radio Resource Management" (RRM), which is *the set of functionalities whose aim is to provide services according to the QoS negotiated for each application over the area covered by the system, and to optimize the system capacity through the choice of the best resource sharing among users* [1] – [5]. Scheduling, together with some other well known functionalities such as Power Control (PC), HandOver (HO), Admission Control (AC), Congestion and Load Control and Link Adaptation (LA), belongs to RRM.

At first, the scheduling issue was addressed during the Fifties, when American industries decided to use the expertise they gained on operational research for military issues, and applied scheduling with the aim of optimizing industrial logistics. From that point in time on, many applications have been identified ranging from industry [6], [7], to computer science [8], [9], from electronics [10] to telecommunications. Due to this versatility of application, generally speaking scheduling could be defined as *the assignment of a limited set of resources among several activities on the temporal axis according to their deadlines*. Scheduling algorithms are, in general: time-constrained, dependent on the maximum capacity and subject to optimization criteria based on queue length, balanced resource sharing, delivery delay and resource assignment cost. Therefore, it could be interesting to identify when a scheduling algorithm can be defined as *optimum*. However, even though it has been proved that in computer science Earliest Deadline First (EDF) is the optimum scheduling strategy for CPU (Central Processing Unit) without energy constraints and in the presence of delay-constrained wired networks [8], [9], the identification of optimum scheduling strategies for wireless systems is still an open issue.

Many definitions for scheduling in wireless systems have been provided over the last fifteen years. For example, in books related to 3G systems, definitions such as "the packet scheduling function shares the available air interface capacity between packet users. The packet scheduler can decide the allocated bit rates and the length of the allocation" according to [11], or, "the main task of the PS (*note:* Packet Scheduling) is to handle all NRT (*note*: Non Real Time) traffic, *i.e.*, allocate optimum bit rates and schedule transmission of the packet data, keeping the required QoS in terms of throughput and delay" [12], are provided. Trying to generalize and to abstract a unique definition, scheduling could be defined as an *RRM functionality performed at the Medium Access Control (MAC) sub-layer, whose aim is to evaluate the set of resources available and distribute them among competing flows according to their priority in order to guarantee the QoS negotiated by flow and network*, where a flow can be defined as one of the possibly several parallel data streams supported by a certain user.

Since in the abovementioned definition the term "resource" is introduced, it would be worth trying to specify what a resource is in the peculiar contest of wireless systems, especially considering that a plethora of them (*e.g.*, mobile telephony, mobile data access, portable communications, etc.) are offered to the end user and possibly coexist. However, providing a general definition of "*radio resource*" is quite hard, since scheduling definition is given regardless of the type of system over which it is performed (in fact, as shown previously, it applies to several disciplines). Thus, this definition could be applied to any kind of wireless system and, hence, to any kind of air interface. In order to generalize this concept to any wireless system, a Radio Resource (RR) could be defined as *the signal format necessary to define how a certain amount of data can be transmitted over the wireless medium*. According to this definition, a specific RR is fully identified by a set of different "dimensions" which vary from air interface to air interface. For example, in a Time Division Multiple Access (TDMA) system, an RR is identified by all the following dimensions: the time slot over which transmission is allowed, the carrier frequency and the relevant bandwidth, the modulation and coding format, the power level and the transmitting spatial dimension. According to the definition of Radio Resource previously provided, a Resource Unit (RU) can be consequently defined as the minimum amount of RR assignable or, alternatively, the RR allowing the minimum amount of data to be transmitted. However, since a RR (and consequently a RU) is composed of both discrete (*e.g.*, time slot) and continuous (*e.g.*, power level) dimensions, it is actually impossible to define a numerable set of resources offered by a certain system. Nevertheless, since sometimes this could be useful, it is a common practice also to use a "reduced" definition of resource intended as the set of only discrete dimensions, and in particular the frequency carrier, the time slot, and the coding sequence in case of Code Division Multiple Access (CDMA) based systems, and the transmitting beam or antenna in case of Space Division Multiple Access (SDMA). In such situation, it is indeed possible to compute the maximum number of resources offered by the system, definable as the maximum capacity of the system. According to this definition, the problem of scheduling is about the distribution of orthogonal resources among competing users, where the orthogonality implies that each resource can be allocated to at most one user. From now on, the term Radio Resource will be used both in its fully comprehensive sense and in the reduced one according to the context.

Having defined the Radio Resource, it is now possible to introduce the concept of Adaptive Radio Resource Assignment, as *the allocation of a specific set of Radio Resources to a certain flow according to the contingent state of the system*. This definition has two main implications: firstly, when performing RR assignment the air interface structure of the system under investigation is known and considered in the process, since it defines the specific format of RRs; secondly, the adaptiveness of the process can be related to one or several time-varying characteristics of the system, such as wireless channel, the state of the queues, the number of users, QoS requirements, the state of some layers in the protocol stack, et cetera. In the literature, the terms "scheduling" and "resource assignment" are often used as synonyms, or interchangeably without a real (or at least clear) distinction. However, according to the definitions provided, it is evident that while scheduling implies resource assignment, the contrary does not hold. In fact the temporal axis and the multiuser dimension are not present in the second, where only instantaneous conditions related to a single user are considered. Only a few works in the literature formalize this distinction, whose potential is high for future wireless systems, as discussed below.

Over the last fifteen years, wireless systems have become more and more complex; consequently, also scheduling complexity has increased. So, some works in the literature [13] – [15] presented a functional split of the whole scheduling process: it can be imagined that the identification of the flows selected for transmission and of the relevant RRs to be allocated, could be performed in different stages, in order to reduce the complexity. According to this definition, it could be noticed that the module responsible for radio resource assignment should obviously be aware of the air interface, since the knowledge of the particular set of resources (frequencies, slots, codes, maximum power allowed, modulation and coding format, etc.) offered to the system and, possibly, of the channel quality perceived by the users, is needed. On the contrary, the scheduling module could be even air interface unaware, since the decision of the particular flow to be served could depend much more on some application-side information such as the state of the buffers or some application requirements. In such a scenario, the knowledge of the air interface structure and of channel dynamicity at the resource assignment module, and of application parameters at the scheduler, allow the real implementation of a cross-layer approach, which is emerging as a hot topic about scheduling for a valuable QoS management. For instance, in [16] the authors present resource allocation as a cross-layer design based on an optimization of MAC layer parameters with an accurate model of the PHY layer.

The aim of WPR.8 over the NoE life will be the integration of research between partners on the design of radio resource assignment and scheduling techniques through the application of new design paradigms, possibly implementing a cross-layer approach, and considering both centralized and distributed systems. The innovative contribution of this WorkPackage is particularly in the fact that the focus of the activities will be not only on the identification of new algorithms, but also (and especially) on the methods to be used in algorithm design. Moreover, efforts will be devoted to the application of scheduling to emerging architectures such as distributed systems, cognitive radio networks, heterogeneous networks, and possibly network coding.

To this aim, the WP is organized in the following three Tasks: "*TR8.1 – Scheduling Techniques for Multi-Carrier and Space Division Systems*", "*TR8.2 – Scheduling Techniques for Self-Organising and Distributed Networks*", "*TR8.3 – Scheduling Techniques for Heterogeneous Networks*", where the definition of scheduling and adaptive radio resource assignment (from now on, denoted also as radio resource allocation) provided in this Section will be applied and adapted according to the different scenarios under consideration. Since emerging wireless systems seem to be Multi-Carrier (MC) and/or SDMA based, it is of primary concern to design resource assignment algorithms suited to such kind of complex air interfaces, and this topic will be addressed by TR8.1. Even though usually scheduling is addressed in cellular systems, where a centralized unit takes decision according to the information collected about each flow, in TR8.2 the scenario addressed will be composed of nodes organized in an infrastructure-less fashion (such as mesh, ad hoc and sensor/actuator networks), where the main issue is the selection of nodes allowed to transmit and the relevant resources without the help of a centralized "omniscient" controller and, hence, where at each node only partial information about the rest of the network is available. Finally, another important issue is the coexistence of several systems simultaneously available to a given user, where it could be beneficial for the user to exploit the diversity and the larger capacity offered by the multiple air interfaces available; so, in this case the main issue will be the identification of common parameters to be used over different kinds of air interface and the definition of suitable metrics to perform scheduling, which will be addressed in TR8.3.

In order to meet the expectations set over the NoE lifetime, mid-term objectives are defined. In particular, the aims of this deliverable will be the following: first of all, the introduction of a common language between partners, through the discussion and identification of definitions to be agreed in the WP. Then, analyses of the State of the Art (SoA) of scheduling in the literature will be provided. This will be also used to make a classification of these algorithms according to the approach implemented (*e.g.*, fairness-oriented, throughput-based, centralized, distributed, game-theory based, etc.), in order to identify what should be saved in design methods of future scheduling strategies. Then, for each Task a set of Joint Research Activities (JRAs) are defined and described, according to the declarations of interest provided by the partners during the first months of NEWCOM++. The identification of the relevant target scenarios to be investigated in each JRA and the relevant types of contribution and outcomes expected will be provided.

As a general objective of each JRA, it is expected to develop methods to design algorithms according to theoretical approaches. In fact, generally most approaches considered in the literature are heuristic methods used to define new scheduling functions, whereas only a few works consider analytic frameworks (typically according to game theory or optimization methods based on utility functions), as it will be shown in the following. Moreover, often scheduling algorithms are claimed to be "optimum" or "robust" [17] – [21], when it is not clearly defined what should be the characteristics and performance of a scheduling algorithm (maximizing capacity? Guaranteeing fairness? Finding the best trade-off between both?). Since it is difficult to compare different algorithms which are implemented in different contexts and with different application types, it is reasonable to define target scenarios; in fact, it would be too ambitious (if not infeasible) to define "the" optimum scheduling algorithm applicable to any kind of system. However, it should be a goal of this WP to define a general framework to evaluate the performance of scheduling algorithms for the specific target scenarios and applications identified in this WP (*i.e.*, how to jointly consider aggregated throughput and fairness? Which metrics should be used depending on different applications?).

The JRAs identified in this WP will be performed by the following partners: CNIT, NKUA/IASA, CNRS, UPC, CTTC, LNT-TUM, UCL. They are expected to contribute to all activities related to the NoE, such as at least one JRA, writing deliverables, attending joint meetings, proposing and organizing joint workshops and special sessions in conferences, organizing summer and winter schools, contributing to NEWCOM++ Vision Book, jointly editing special issues.

Finally, interactions with other WPs of the NoE are desirable and will be fostered by the participation of some partners to several WPs. Natural interaction will be carried out with WPR.9 "*Joint RRM and Flexible Use of Radio Spectrum*", WPR.10 "*Network Theory*" and WPR.11 "*Opportunistic Networks*", since all these three WPs belong to the Network Cluster. Moreover, it is also expected cooperation with WPR.2 "*Feedback and Resolution of the Channel State*" and WPR.5 "*Coding for Multi-Hop Wireless Networks*", which could provide useful inputs to WPR.8 activities.

2. State of the Art on Scheduling and Adaptive Radio Resource Assignment for Wireless Networks

In this Section an overview of the main scheduling techniques published in the literature will be provided. Clearly there is no pretension of completeness, since over the last fifteen years hundreds of papers have been published on this topic. Trying to find a way to group them is not easy, since most of them are designed according to different heuristics, refer to different systems (*i.e.*, air interfaces), support different applications, implement different approaches, use different evaluation metrics. However, since many algorithms are heuristic adaptations or simplifications of a few commonly agreed approaches (*e.g.*, optimization problem or game theory), in this Section these basic approaches will be identified and described. Moreover, it could be noticed that the State of the Art (SoA) related to multi-carrier based systems is larger than those related to distributed and heterogeneous networks. This should be expected since, as it will be clarified later, the literature on multi-carrier systems is more mature, whereas those about distributed and heterogeneous networks are still in an embryonic stage [16]. However, since one of the objectives of this deliverable is to provide a classification of the different algorithms according to the aim they pursue (*e.g.*, throughput maximization, fairness guarantee, etc.) or the approach implemented (*e.g.*, cross-layer, heuristic or theoretical, etc.) in order to identify proper design tools and methods for scheduling in future wireless systems, as a preliminary step, a detailed survey of scheduling algorithms related to the specific Tasks addressed in this WP will be provided.

2.1 SoA – General Overview

The convergence between mobile and data access internet-based services posed specific challenges to wireless networks designers about how to exploit the set of resources available as efficiently as possible. In fact, since the only application supported was voice, RRM was not crucial until 2G, whereas network planning had a fundamental role. Thus, the conventional approach used was "*divide and conquer*" based, with the following meaning:

- in the *divide* phase, network resource planning was applied to fragment the network area into smaller zones isolated from each other from an electromagnetic point of view. In cellular systems, the cluster concept was introduced, defined as the set of cells over which the whole resource budget is used, and for a given cluster a certain radio resource could be used only once. In ad-hoc networks, isolation of transmit-receive pairs from each other was performed by means of carrier sensing based MAC protocols;
- in the *conquer* phase, the loss of link efficiency due to interference for a given cell (or for a local transmit-receive pair in ad-hoc networks) was compensated via the introduction of specific techniques such as efficient Forward Error Correction (FEC) coding, fast link adaptation protocols, multiple-antenna transceivers [22] and channel aware scheduling strategies [23].

However, the need for high spectral efficiency led system designers towards an aggressive spectral reuse, giving an increased interference in the network in spite of power control and dynamic resource allocation. Moreover, multi-cell resource planning and power control were traditionally designed to reach an SINR target simultaneously for all interfering terminals, aiming at allowing users to operate under a common minimum Carrier-to-Interference level (*C/I*), defined according to the receiver's sensitivity or a preset operating point at the user terminals (access points). This *SINR balancing* approach ensured the worst-case outage probability necessary for connection-oriented voice calls [24] – [26].

Nowadays, the concept of a specific operating point is becoming less relevant and network planning phase has no sense without RRM, since modern networks are supposed to support and manage different QoS requirements in the presence of mixed traffic composed of possibly Real Time (RT) and Non-Real Time (NRT) applications. This should be done taking into account the intrinsic time-variant and frequency-selective nature of the wireless channel, which results in highly bursty errors, time-varying capacity and different throughput and delay values experienced by each user within the system according to the currently perceived channel quality. For these reasons, it is clear that, while fulfilling

QoS requirements, scheduling should also maximize system usage and, thus, the aggregated throughput, while trying to guarantee some fairness among differently located users. Moreover, current systems typically feature Adaptive Modulation and Coding (AMC) schemes, aiming at maximizing the *sum network capacity*, defined as the sum of simultaneous transmit-receive link capacities, which appears as a meaningful metric. Due to the issues abovementioned, the limitation of the divide and conquer approach applied to network-wide performance optimization is clear.

So the first idea explored by researchers dealing with wireless scheduling was the exploitation of channel variability through the so called "opportunistic scheduling" [27]. The aim of such algorithm is the maximization of system throughput by serving always the user(s) with the best channel conditions, realizing the so called multiuser diversity [28], *i.e.*, the independence of random channel fluctuations experienced by each user in the system. However, it is worth noting that this gain can be realized only if link adaptation techniques are available to take advantage of the improvement in channel conditions. This technique has the advantage of maximizing throughput and spectral efficiency, which is crucial in wireless systems due to spectrum scarcity, but it has an important drawback in its unfairness, since users affected by poor channel conditions may starve for long time. Currently, some works [21] have been carried out in order to incorporate QoS constraints into opportunistic schedulers; thus, trading off multiuser diversity and user satisfaction.

In order to provide fairness among users, in [29] it was shown that it can be at least partially restored by modifying the scheduling criteria in one of several possible manners. Moreover, many new algorithms were proposed, which can be grouped into two categories. The main algorithms in the first category which could be recognized are: the Proportional Fair (PF) scheduling [30] – [32], whose aim is maximizing throughput provided that long-term fairness is guaranteed; strategies like Max – Min Fairness, Weighted Max – Min Fairness, Purely Fair Scheduling, Wireless Adapted Fair (WAF) scheduling, could be considered as enhanced versions of PF scheduling. The second category is based on the concept of *leading* and *lagging* flows, where *lead* is defined as the amount of service that a flow, having experienced good channel quality until the current instant, should release in favour of "unlucky" users, whereas *lag* is the amount of service a flow should receive due to the fact that it has experienced bad channel quality until the current instant. Obviously, a flow could be either leading or lagging, not both simultaneously. The main strategies based on this approach are the following: Wireless Fair Service (WFS) [33], Idealized Wireless Fair Queuing (IWFQ) [34], Channel condition Independent Fair Queuing (CIF – Q) [35], Server Based Fairness Approach (SBFA) [36]. However, also these strategies suffer from some important limitations: in particular, they do not support short-term fairness since transmission is always subjected to good channel conditions, they are based on very simplified channel quality evaluations such as only "*good*" and "*bad*", leading users may be affected by ungraceful service degradation since they can be excluded from transmission for long time, which is critical in case RT applications should be supported.

The two large categories presented above, which could respectively be defined as "*totalitarian*" and "*egalitarian*" as well identified in [37], were initially applied to TDMA air interfaces and in the presence of simplified traffic models such as buffers always full, no delay requirements, no service differentiation, et cetera. Moreover they considered ideal channel knowledge, which is an unrealistic assumption due to the channel random behaviour and could lead to bad performance when implemented in real systems. So, a step further was performed in order to consider the incompleteness of channel knowledge. For example, in [38] – [40] some probabilistic models where used to introduce and manage channel variability, even though most of them are based on Markov chains, which were proven to be not satisfactory for channel modelling [41].

2.1.1 The Advent of Multi-Carrier Based Systems

More recently, service differentiation in advanced communication systems has been identified as a relevant issue to be addressed. So, different more complex statistics were introduced to take into account the different behaviour of multimedia traffic sources [39], [42], [43], and more complex air interfaces, which could be multi-carrier and possibly Multiple Input Multiple Output (MIMO) based

[13], [15], [44], [45], were considered. In particular, Orthogonal Frequency Division Multiple Access (OFDMA) has been indicated as the candidate access technology for future wireless systems such as WiMAX [46] and UMTS LTE [47], due to some interesting properties such as wideband communications, flexibility in allocation and supportable bit rates, robustness against interference and frequency selective fading, high spectral efficiency, ease of implementation [48] and, especially for scheduling, multiuser diversity, *i.e.*, the capacity of exploiting the channel fluctuations observed by more than one user in the allocation process. Due to the relevance of such kind of systems, an entire Task of this WP is devoted to the study of methods to design algorithms for this kind of systems. Moreover, cross-layer implementation of scheduling functionality is raising more and more interest, since the exploitation of information coming also from non adjacent layers of the protocol stack (*e.g.*, the application layer) could be beneficial when selecting which user should be allowed to transmit [13], [43], [44].

There are a number of different ways to take advantage of multiuser diversity in OFDMA systems. The idea is to develop algorithms to determine which users to schedule, how to allocate subcarriers to them, and how to determine the appropriate power levels for each user on each subcarrier. Referring to a downlink OFDMA system, usually users estimate and feedback the Channel State Information (CSI) to their base station, where subcarrier and power allocation is determined according to users' CSI and the resource allocation procedure. Once the subcarriers for each user have been determined, the base station must inform each user about the result of the allocation process. This subcarrier mapping must be broadcast to all users whenever the resource allocation changes. Typically, resource allocation must be performed with timing on the order of the channel coherence time, although it may be performed more frequently if there are many users competing for resources. Resource allocation is usually formulated as a constrained optimization problem, to either:

– minimize the total transmit power with a constraint on the user data rate [49], [50];
– maximize the total data rate with a constraint on total transmit power [51] – [54];

where the first objective is appropriate for fixed-rate applications (*e.g.*, voice), while the second is more appropriate for bursty applications like data and other Internet Protocol (IP) based services.

As a first comment on scheduling techniques published in the literature, it can be noticed that most of the works are based on heuristic methods: each work proposes algorithms designed according to reasonable considerations trying to take into account as many characteristics as possible. Only a few papers try to use theoretical frameworks for the definition of scheduling techniques, mainly because they are too complex to be handled in a few milliseconds, as it will be clarified in the Section dedicated to scheduling in MC-based systems. In this case, the most used strategies are based on optimization through utility functions [39], [55], [56], and tools borrowed by economics, such as game theory [57], [58], and auction based algorithms [59], [60].

2.1.2 From Single-Cell to Multi-Cell Scenario: Controlled and Distributed Approach

All the strategies abovementioned were designed to be implemented as a centralized functionality to be performed at the Base Station Controller (BSC) in 2G systems and in the Radio Network Controller (RNC) in 3G systems, or at the base station. So, many of the scheduling algorithms published in the literature implement a *centralized* approach. Due to the implementation in more recent systems such as High Speed Packet Access (HSPA) and LTE of fast scheduling (in the order of very few milliseconds) and LA, scheduling function has been moved in Node-B directly. However, while the centralized approach is optimal from the single-cell point of view, since some kind of "god" aware of everything happening inside his cell can take decision in the best possible way, this could be not true in a multi-cell environment. In fact, if every cell takes decision autonomously, it is possible that problems with intercell interference rise. In this case, it could be beneficial to implement a *coordinated* approach among the different Node-B, in order to perform a joint optimization of resources in all cells simultaneously, thus keeping under control interference in the network. This could be achieved through the introduction of a central control unit able to gather information from and coordinate several cells. Such a joint multi-cell resource allocation offers an enormous number of degrees of freedom governed by the number of cells, times the number of users, times the number of possible scheduling slots, codes, power levels et cetera [61].

Obviously, the potential in coordinated resource allocation across cells also results in several practical issues such as slot level synchronization for large network areas, which can be partly alleviated by clustering the optimization, and joint processing of traffic and channel quality parameters fed back by all network nodes to a central control unit, leading to request of high computational power and huge signalling overhead. Even though global network coordination is hard to realize in practice, some recently published and promising methods showed how some multi-cell coordination gain may be realized with limited complexity and/or limited centralized control [62] – [68]. In particular, three leading and independent strategies may be identified in the literature toward making multi-cell resource coordination more practical, and they will be described in the following.

Since one of the major difficulties related to interference avoidance is the lack of predictability of interference coming from other links due to the burstiness of the traffic and the temporal channel variability, *structuring* could be a good approach to be enforced on the resource planning grid to make interference more predictable. In [62] and [63], a particular power shaping of the time frame in the joint user scheduling and power allocation problem was exploited: the Access Point (AP) transmits with different powers in different portions of the frame, and users are allotted slots according to the amount of interference they can tolerate given their channel conditions. Analogously, in [64] Time-Slot Resource Partitioning is proposed, according to which power shaping over the cell sectors is implemented by turning off sector beams according to a determined sequence. In another approach, structure may be enforced by fixing the order in which time/frequency slots are being filled up with user packets. For underloaded systems, a predictable average portion of the slots remain unused and the location of such slots on the multi-cell resource grid can be optimized to reduce interference for selected users [65]. As shown in [66], the spatial position of users in the cell can also be used to coordinate intercell transmissions to avoid excessive interference. Such clever resource planning schemes are interesting, since they offer additional flexibility in mitigating interference with very low complexity and little need for signalling, but they are not fully exploiting the degrees of freedom provided by the joint multi-cell resource allocation problem, as the imposed structure tends to reduce the dimensions offered in the optimization.

Since certain quantities in the resource allocation problem may be continuous, a potentially interesting tool consists of *discretization* of the optimization space, to reduce the number of potential solutions and also to reduce the feedback rate needed to communicate overhead data between nodes. For instance, when the spatial dimension is used, so far, the discretization of the optimal beamforming weights through the use of vector precoding has been proposed mostly for the single cell scenario for the purpose of feedback reduction as in [67]. In the case of beamforming weights, discretization can be applied posterior to beamforming weight computation. In the case of power control, discretization can be carried out prior to optimization, to simplify the power level search procedure. Remarkably, the discretization of power control, even to its extreme of binary on/off control, can be shown to yield quasi-optimal results in a number of cases [68].

Due to the non-convexity of many of the multi-cell resource optimization problems, finding globally optimal solutions is difficult and an analytical formulation of the solution is often infeasible. While *greedy search* techniques have been popularized over the last few years in the area of resource allocation in multiuser SDMA [69] – [71], and OFDMA scheduling [72], [73], their application to multi-cell resource allocation seems to have drawn attention only recently. In this case it operates by optimizing on a cell by cell basis, sequentially, just as individual users are optimized sequentially in the single cell scenario. At each cell visited, the resource is optimized based on local channel conditions and newly updated interference conditions originating from the other cells [74], [75]. Such techniques may also be applied in an *iterative* manner by revisiting a sequence of cells several times until capacity convergence is reached.

Another important issue is the coordination of resource allocation over different coexisting air interfaces, considering the implementation of Common Radio Resource Management (CRRM) strategies. In fact, a plethora of wireless systems is now offered to users, and possible cooperation among them will lead to the so called *trunking gain* [76]. In the literature different approaches were proposed, ranging from loose coupling, according to which a common authentication mechanism among different air interfaces is allowed, to very tight coupling, according to which one of the air interfaces is seen actually as part of the other network [77], [78]. It is clear that a very strong interaction is required for joint allocation performed over different air interfaces. Although the problem has been under investigation for some years already, it is still far away from being solved, and before designing appropriate scheduling strategies across multiple air interfaces, it is still necessary to study and identify good Vertical Handover (VHO) techniques, which are a fundamental preliminary step.

At first sight, joint multi-cell resource allocation and scheduling do not lend themselves easily to *distributed* optimization, because of the strong coupling between the locally allocated resources and the interference created elsewhere in the network. Hence the maximization of cell capacities taken individually will not in general result in the best overall network capacity. Nevertheless, over the last years, beside the classical cellular systems, some other paradigms are emerging, such as ad hoc networks and cognitive radio. In such kinds of network it is difficult to imagine some coordination, since it requires the definition of a control unit. Moreover, they are composed of nodes which can appear and disappear also frequently. In this situation a distributed approach is mandatory. In Figure 1 and Figure 2 the difference between a controlled and a distributed architecture in multi-cell scenario is reported. It can be noticed that in a controlled approach, there is a dedicated unit which collects information from each cell, and uses them to take decision about allocation in each cell under its control, thus also managing interference in the network; whereas in case of distributed approach, each cell takes decision autonomously about allocation, thus, some interference may occur, as emphasized in Figure 2.

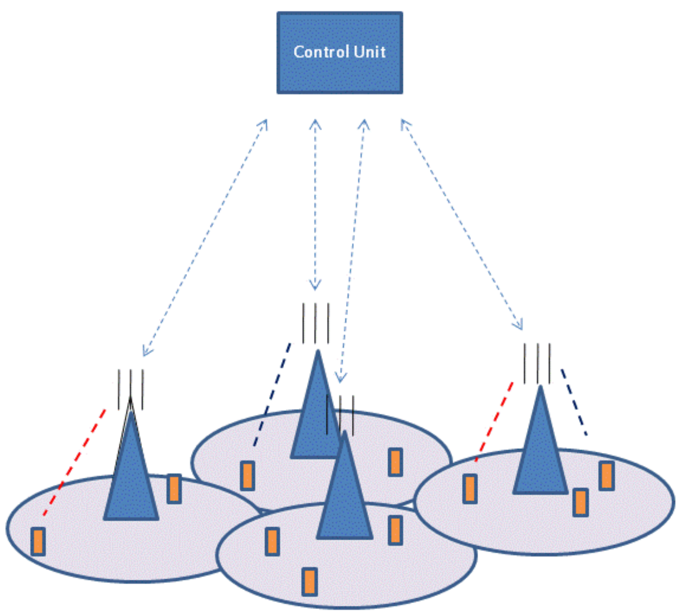

Figure 1: Controlled Approach in Multi-Cell Scenario

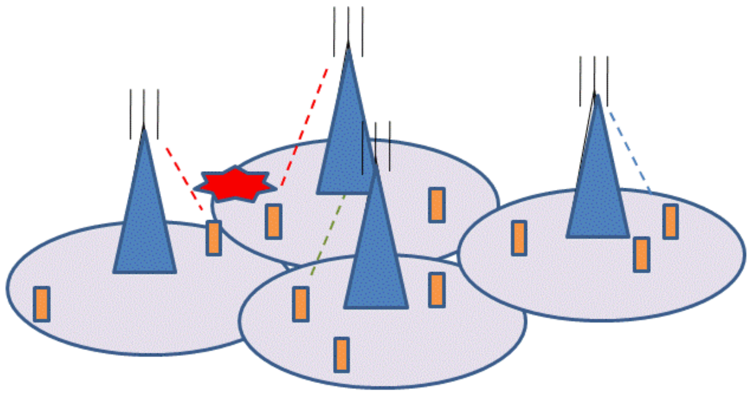

Figure 2: Distributed Approach in Multi-Cell Scenario

Despite the fact that the ad hoc network concept is not new, the design of scheduling algorithms for this kind of networks has been emerging only recently, since traditionally Carrier Sensing Multiple Access (CSMA) based strategies were implemented, because ad hoc networks are characterized as peer-to-peer, and channel access should happen in a distributed way. This poses new challenges, such as the partial knowledge of the rest of the network at each node and, in extreme situations, the totally blind allocation process. The problem shows such a complexity that it is still difficult to find in the literature some works dealing with scheduling in ad hoc networks [79] – [81]. However, due to the always increasing demand of multimedia applications, it is hard that CSMA can cope with complex QoS management.

Among the very few works about scheduling over distributed systems, an approach relies on the idea that interference behaviour can be made more predictable by making the network larger or denser and, consequently, the resource allocation problem in a given cell is made more dependent on the local channel conditions in that cell, thus facilitating distributed optimization [82]. Moreover, some interesting asymptotic results dealing with the case where the number of users per cell is sufficiently large can be mentioned. Indeed in this case, it can be shown that although the complexity of multi-cell scheduling and resource allocation seems to grow exponentially large, under the effect of sum capacity maximizing scheduling, intercell interference tends to vanish, making distributed resource allocation much simpler than in the small number of users case [83]. However, while cellular systems already show a wide literature about scheduling, the potential of scheduling over distributed networks is still largely unexplored, and for this reason the state of the art about scheduling over distributed network is still in a very preliminary phase.

2.1.3 A New Emerging Paradigm: Cognitive Radio

Cognitive radio deserves special attention, since it is a new paradigm in wireless communications to enhance utilization of the limited spectrum resource. It is defined as a radio able to utilize available side information and to change its transmitter parameters based on the interactions with the surrounding environment where it operates, in order to efficiently use the radio spectrum. The basic idea is that a cognitive radio is able to properly sense the spectrum conditions and, to increase efficiency in spectrum utilization, it seeks to underlay, overlay or interweave its signals with those of the primary, licensed users, without impacting their transmission [84].

In cognitive radio networks, a hierarchical model is defined where Primary Users (PUs) are entities characterized by a higher priority in a given frequency band (*e.g.*, cell phones, TV stations, emergency service, etc.) than secondary users (SUs). PUs are not cognitive radio aware, that is, they are not able to facilitate signalling information to SUs to allow the access in their frequencies. On the other hand, Secondary Users (SUs) are characterized by cognitive radio capabilities, that is, in order to access certain frequencies, a SU has to continually monitor the radio spectrum to identify spectrum opportunities, to reliably detect the presence of PUs, and to evaluate the interference the SUs transmitter may cause on the PUs receivers. This process is known as *spectrum sensing*.

Different architectures, both centralized and decentralized, have been proposed in literature for cognitive radio networks. IEEE 802.22 is the first worldwide standard based on the cognitive radio technology [85], [86]. In this context a centralized architecture is proposed where a base station manages its own cell and all the associated users. Another example of centralized architecture is DIMSUMnet [87], where a centralized network level brokering mechanism is implemented. In [88], a centralized spectrum pooling architecture is proposed based on Orthogonal Frequency Division Multiplexing (OFDM). On the other hand, since the availability of channels changes over time and space according to the presence of PUs and SUs, distributed control plans in an ad hoc fashion have also been proposed to reduce signalling and infrastructure costs of the secondary network. For example, CORVUS [89] is based on local spectrum sensing, where PU detection and spectrum allocation are performed based on the coordinated and collaborative operation of SUs. Additionally, the Nautilus project proposes a distributed, scalable and efficient coordination framework for open spectrum ad hoc networks, which accounts for spectrum heterogeneity while not relying on the existence of a pre-defined common channel for control traffic [90]. So, it is clear that in such kind of network, distributed approach is more natural in scheduling implementation.

Spectrum scheduling is a rather important but almost unexplored issue in cognitive radio networks, since it is in charge of properly managing the radio spectrum and scheduling SUs in available primary frequency channels based on the results collected during the spectrum sensing. The main objectives of spectrum scheduling are:

- guarantee effectiveness in the secondary usage of spectrum;
- not cause harmful interference on the PUs receivers through SUs' communications;
- meet, as much as possible, the SUs communications requirements;

to this end, the information collected during the spectrum sensing operation is analyzed, the available spectrum bands are characterized (*spectrum analysis*) and the best available channel is selected for transmission by SUs (*spectrum decision*). Additionally, if a PU is detected and if the SU is causing harmful interference to it, the frequency channel has to be quickly vacated initiating the process of the so called *spectrum handoff* [91].

With respect to self-organized networks, it is worth mentioning that band and channel scheduling approaches have also been proposed for Wireless Mesh Networks (WMN) [92]. In particular, in [92], besides a novel spectrum sensing method that allows identifying primary user frequencies without additional transceivers and changing the de facto IEEE 802.11 standard for WMNs, an analytical model to estimate the interference caused in a given point, due to a cluster operation is presented, which is used to decide channel and band allocations.

2.1.4 Interaction with Other Functionalities: the Potentialities of Network Coding

The interaction of scheduling with other functionalities could be fundamental to achieve better system performance. It was already said that joint scheduling and LA can fully exploit multiuser diversity, and that joint VHO and scheduling is necessary for cooperation among different air interfaces. However, it should be also mentioned that another concept has been emerging over the very last years as a hot topic in multicast system, which is *network coding*. While the literature on network coding is now quite extensive as shown in the long reference list in [93], works that explicitly considers medium access issues and that attempts to find optimal medium access policies, which may be random or deterministic, are relatively rare. In particular, the medium access approaches considered fall into three categories, all introduced before network coding: deterministic time- or frequency-division, deterministic code-division, and random time- or frequency-division.

In deterministic time- or frequency-division, nodes are assigned with time slots or frequency slots according to a deterministic schedule that aims to avoid simultaneous transmissions from neighbouring nodes in the same time or frequency slot [94]. Finding optimal solutions to this problem has been shown to be NP-complete (Non-deterministic Polynomial-time complete), so the emphasis is on finding good heuristics. These heuristic solutions generally attempt to find optimal ways of scheduling among a subset of the valid transmission assignments, which are chosen to be "*good*" according to some criterion (*e.g.*, each element of the subset is maximal in the sense that no more nodes can be assigned to transmit without causing collisions). In the network coding literature, this approach is taken in [95] – [97].

In deterministic code-division, nodes are assigned power levels at which to transmit for given time intervals. It is then assumed that, presumably through the use of CDMA, nodes can communicate with each other at a rate that is a function of their SINR. Provided that this rate function is concave, this approach generally leads to a tractable convex optimization problem. The approach is discussed, with consideration given to network coding, in [98], where a distributed algorithm for performing the relevant optimization is proposed.

In random time- or frequency- division, nodes transmit according to an assigned probabilistic rule, which may simply determine whether a node is or is not transmitting in a given slot, or may also determine transmission power. Finding these probabilistic rules is often easier than finding deterministic assignments, and probabilistic rules are often easier to implement since less coordination is required among nodes. Moreover, such random medium access is well-suited to network coding, because network coding naturally provides robustness against collisions, and does not require the overhead of per-hop acknowledgments. Random medium access, in conjunction with network coding, is discussed briefly in [99] in the context of a simple example.

Finally, SDMA relaying on MIMO techniques could also be applied to network coding in order to exploit the spatial diversity inherent in packet combining. This is possible because network coding and MIMO solve similar problems, namely to decode a vector of transmitted symbols given a vector or received samples. The aim would be to make the system more robust than traditional network coding to fading and packet losses.

As noted, none of these medium access approaches are new; moreover, the introduction of network coding does not fundamentally change any of them. However, network coding changes the link rates that are demanded to a medium access strategy. So, though no fundamental changes are required, the strategy must be optimized with network coding in mind because link-rate demands under network coding differ substantially from those under traditional routing. Qualitatively, network coding prefers the broadcasting of a packet to several neighbours rather than transmission to a single neighbour, whereas traditional routing is almost neutral to this, and copes better with unreliability than traditional routing. Therefore, if the medium access problem for wireless networks is approached without explicit consideration of network coding, then a good solution for the overall coded network is unlikely to result.

In the next subsections, the abovementioned topics will be deeper investigated taking into account the organization of this WP. In particular, since each Task is devoted to the study of scheduling algorithms and methods related to a specific area, the analysis will be conducted in a separate way for each Task.

2.2 SoA related to Task 1: Scheduling Techniques for Multi-Carrier and Space Division Systems

Over the last years many works were published about scheduling in multi-carrier based systems. This happened because of the very interesting characteristics of this kind of air interface. Moreover, since it is typically implemented over cellular based wireless systems, many of the algorithms published are extensions of strategies designed for TDMA based systems.

2.2.1 Maximum Sum Rate Algorithm

The objective of the Maximum Sum Rate (MSR) algorithm is to maximize the sum rate of all users, given a total transmit power constraint [53]. This algorithm is optimal if the goal is to get as much data as possible through the system. The drawback of the MSR algorithm is that it is likely that a few users that are close to the base station, having excellent channels, will be allocated all the system resources. The SINR for user k in subcarrier l can be expressed as:

$$SINR_{k,l} = \frac{\dfrac{P_{k,l}}{L_{k,l}}}{\sum_{\substack{j=1 \\ j\neq k}}^{K} \dfrac{P_{j,l}}{L_{j,l}} + N\dfrac{BW}{N_{sc}}}, \tag{1}$$

where $P_{k,l}$ denotes the transmitted power of the l-th subcarrier to the k-th user, $L_{k,l}$ is the related path loss, N is the noise power over the whole frequency bandwidth (BW) and N_{sc} is the total number of subcarriers. Based on the Shannon capacity formula, the MSR algorithm maximizes the quantity:

$$\max\left\{\sum_{k=1}^{K}\sum_{l=1}^{L}\frac{BW}{N_{sc}}\left(1+SINR_{k,l}\right)\right\} \text{ subject to } \sum_{k=1}^{K}\sum_{l=1}^{L}P_{k,l} \le P_{\max}. \tag{2}$$

The sum capacity is maximized if the total throughput in each subcarrier is maximized. Hence, the max sum capacity optimization problem can be decoupled into N_{sc} simpler problems, one for each subcarrier. Further, the sum capacity in subcarrier l, denoted as C_l, can be written as:

$$C_l = \sum_{k=1}^{K}\log\left(1+\frac{P_{k,l}}{P_{\max,l}-P_{k,l}+N\cdot L_{k,l}\cdot\dfrac{BW}{N_{sc}}}\right), \tag{3}$$

where the difference $P_{max,l} - P_{k,l}$ denotes other users' interference to user k in subcarrier l. It is easy to show that C_l is maximized when all available power $P_{max,l}$ is assigned to just the single user with the largest channel gain in subcarrier l. This result agrees with intuition: give each channel to the user with the best gain in that channel. This is sometimes referred to as a "greedy" optimization. The optimal power allocation proceeds by the waterfilling algorithm, and the total sum capacity is readily determined by adding up the rate on each subcarrier.

2.2.2 Minimum Transmit Power

Another possible approach is to assign resources with the goal of minimizing the overall transmitted power in the system under different rate constraints for each user [100], [101]. This approach can be easily formulated as a Linear Programming (LP), under the assumption that the perceived SINR for each user is known when performing allocation. As for the Maximum Sum Rate algorithm, the feasibility of this approach depends on the accuracy of the SINR measurements, and it is hardly feasible in fast fading environments.

2.2.3 Maximum Fairness Algorithm

Although the total throughput is maximized by the MSR algorithm, in a cellular system like WiMAX, where the path loss attenuation will vary by several orders of magnitude between users, some users will be extremely underserved by an MSR-based scheduling procedure. At the opposite extreme, the maximum fairness algorithm [102] aims at allocating subcarriers and power in such a way that the *minimum* user's data rate is maximized. This essentially corresponds to equalizing the data rates of all users, hence the name "Maximum Fairness". The Maximum Fairness algorithm can be referred to as a *Max-Min* problem, since the goal is to maximize the minimum data rate. The optimum subcarrier and power allocation is considerably more difficult to determine than in the MSR case because the objective function is not concave and, in particular, it is a NP-hard problem to simultaneously find the optimum subcarrier and power allocation. Therefore, low-complexity suboptimal algorithms are necessary, where subcarrier and power allocation are done separately.

A common approach is to assume initially that equal power is allocated to each subcarrier, and then to iteratively assign each available subcarrier to the low-rate user with the best channel on it [102], [103]. Once this generally suboptimal subcarrier allocation is completed, an optimum power allocation according to waterfilling can be performed. It is typical for this suboptimal approximation to be very close to the performance obtained with an exhaustive search for the best joint subcarrier-power allocation, both in terms of fairness achieved and total throughput.

2.2.4 Proportional Rate Constraints (PRC) Algorithm

A weakness of the Maximum Fairness algorithm is that the rate distribution among users is not flexible. Further, the total throughput is largely limited by the user with the worst SINR, as most of the resources are allocated to that user, which is clearly suboptimal. In a wireless broadband network, it is likely that different users require application-specific data rates that vary substantially. A generalization of the Maximum Fairness algorithm is the Proportional Rate Constraints (PRC) algorithm, whose objective is to maximize the sum throughput, with the additional constraint that each user's data rate is proportional to a set of pre-determined system parameters $\{\beta_k\}_{k=1}^{K}$.

Mathematically, the proportional data rate constraints can be expressed as:

$$\frac{R_1}{\beta_1} = \frac{R_2}{\beta_2} = \ldots = \frac{R_K}{\beta_K} \tag{4}$$

where the *k*-th user's achieved data rate is equal to:

$$R_k = \sum_{i=1}^{N_{sc}} \frac{a_{i,k}}{N_{sc}} \log\left[1 + \frac{\frac{P_{k,l}}{L_{k,l}}}{N\frac{BW}{N_{sc}}}\right], \tag{5}$$

where $a_{i,k}$ is '1' when the subcarrier is used by the *k*-th user and '0' otherwise. Clearly, this is the same setup as the Maximum Fairness algorithm if $\beta_k = 1, \forall k$. The advantage is that any arbitrary data rate can be achieved by varying the $\{\beta_k\}_{k=1}^{K}$ values.

The PRC optimization problem is also generally very difficult to solve directly, since it involves both continuous variables $P_{k,l}$ and binary variables $a_{i,k}$, and the feasible set is not convex. As for the Maximum Fairness case, a prudent approach is to separate the subcarrier and power allocation procedure, and to settle for a near-optimal subcarrier and power allocation that can be achieved with manageable complexity. The near optimal approach is derived and outlined in [104] and [105], and a low-complexity implementation is developed in [103].

2.2.5 Proportional Fairness (PF) Scheduling

The three algorithms discussed so far attempt to *instantaneously* achieve an objective like the total sum throughput, equal data rates amongst all users, or pre-set proportional rates for each user. Alternatively, one could attempt to achieve such objectives over time, which provides significant additional flexibility to scheduling algorithms. In this case, in addition to throughput and fairness, a third element enters the trade-off, which is *latency*. In an extreme case of latency tolerance, the scheduler could simply wait for the user to get close to the base station before transmitting. In fact, the MSR algorithm achieves both fairness *and* maximum throughput if the users are assumed to have the same average channels in the long term (on the order of minutes, hours, or more), and there is no constraint with regards to latency. Since latencies even on the order of seconds are generally unacceptable, scheduling algorithms that balance latency and throughput and achieve some degree of fairness, are needed. The most popular framework for this type of scheduling is Proportional Fairness scheduling [31], [32].

PF scheduler is designed to take advantage of multiuser diversity, while maintaining comparable long-term throughput for all users. Let $R_k(t)$ denotes the instantaneous data rate that user k can achieve at time t, and $T_k(t)$ be the average throughput for user k up to time slot t. The proportional fairness scheduler selects the user, denoted as k^*, with the highest $R_k(t)/T_k(t)$ for transmission. In the long-term, this is equivalent to selecting the user with the highest instantaneous rate relative to its mean rate. The average throughput $T_k(t)$ for all users is then updated according to:

$$T_k(t+1)=\begin{cases}\left(1-\frac{1}{t_c}\right)T_k(t)+\frac{1}{t_c}R_k(t), k=k^* \\ \left(1-\frac{1}{t_c}\right)T_k(t), k\neq k^*\end{cases}. \tag{6}$$

Since the Proportional Fairness scheduler selects the user with the largest instantaneous data rate relative to its average throughput, "*bad*" channels for each user are unlikely to be selected. On the other hand, users that have been consistently underserved receive scheduling priority, which promotes fairness. Parameter t_c controls the latency of the system. If t_c is large, then the latency increases, with the benefit of higher sum throughput. If t_c is small, the latency decreases since the average throughout values change more quickly, at the expense of sum throughput. The Proportional Fairness scheduler has been widely adopted in packet data systems such as HSDPA and 1xEV-DO, where t_c is commonly set between 10 and 20. One interesting property of PF scheduling is that as $t_c\rightarrow\infty$, the sum of the logs of the user data rates is maximized. That is, PF scheduling maximizes $\sum_{k=1}^{K}\log(T_k)$.

Although the Proportional Fairness scheduler was originally designed for a single channel time-slotted system, it can be adapted to an OFDMA system by treating each subcarrier independently. In an OFDMA system, due to the multiple parallel subcarriers in the frequency domain, multiple users can transmit on different subcarriers simultaneously. Let $R_k(t, n)$ be the supportable data rate for user k in subcarrier n at time slot t. Then for each subcarrier, the user with the largest $R_k(t, n)/T_k(t)$ is selected for transmission. Let $\Omega_k(t)$ denote the set of subcarriers in which user k is scheduled for transmission at time slot t. Then the average user throughput is updated as:

$$T_k(t+1)=\left(1-\frac{1}{t_c}\right)T_k(t)+\frac{1}{t_c}\sum_{n\in\Omega_k(t)}R_k(t,n), \tag{7}$$

for $k = 1, 2,\ldots,K$. Other weighted adaptations and evolutions of PF scheduling for OFDMA are also possible.

Extending these commented strategies to systems with multiple transmit and receive antennas, *i.e.*, MIMO-OFDMA is also one of the goals of this Task [106]. The extension is straightforward as long as the objective function is separable across the subcarriers. However, it is not an easy task to develop efficient algorithms that group subcarriers and spatial dimension in a wise way in order to provide with agile scheduling. The spatial dimension introduces an additional degree of freedom in resource management, and practical MIMO-OFDMA applications and strategies are still challenging because further studies seem needed to get a deeper understanding of the related tradeoffs and system gains (number of antennas, choice of algorithm, etc.):

- when using the spatial dimension, one problem is that quality measurements, as for instance SINR, depend, among other things, on the number and spatial positions of other terminals being simultaneously scheduled along with the user making measurement;
- feedback for the CSI at the transmitter, but also signalling of scheduling decisions to the terminal, introduce a non negligible overhead and latency in the system, which must be carefully weighed against the capacity gains expected from such techniques;
- the impact of realistic traffic models and system loads, especially on schemes relying on high user loads (*i.e.*, random beamforming) should be investigated. In recent wireless systems based on MIMO-OFDMA (IEEE 802.16e), opportunistic scheduling can be performed in up to three dimensions, namely, time, frequency, and space. Different types of traffic are likely to have different constraints with respect to the available degrees of freedom for the scheduler. It may be wondered how many effective users are available for selection by the scheduler in each of these dimensions, and how to take advantage of the different degrees of freedom to satisfy the QoS constraints for different types of traffic.

2.3 SoA related to Task 2: Scheduling Techniques for Self-Organising and Distributed Networks

Distributed approach in scheduling is a rather new topic, since typically in distributed environments random access is implemented. Some works exist in the literature where distributed scheduling is proposed, and they typically present game theoretic approach, due to distributed nature of the tool. Moreover, due to the peculiar characteristics of the cognitive radio paradigm, a special Section is devoted to it.

2.3.1 Game Theory

An interesting and recently explored path toward enforcing a distributed control of resources has been through the use of game theoretic concepts. Game theory, in its non-cooperative setting, pitches individual players in a battle, each seeking to maximize a utility function by selecting one of several available strategic actions. In the resource allocation framework, users can be terminals competing for access in a single cell, or interfering transmit-receive pairs of a multiple cell or an ad hoc network. The actions may be resource allocation strategies, and the utility may be capacity related. Non-cooperative game models allow transmit-receive pairs to maximize their capacity under reasonable guesses of what competing pairs might be doing [107].

The game theoretic framework is very well suited to network scenarios where infrastructure is sparse or completely absent, as in peer-to-peer and ad hoc networks. As an alternative to the traditional game theory approach above, it was recently proposed to exploit the so-called cooperative games, in which the players essentially build trust into one another, with the aim of improving their own rate, via some form of bargaining. In the recent literature, the application of cooperative games was limited to spectrum sharing in cognitive radio, and in the case of the cooperative beamforming [108] – [110]. However, it was also used earlier in the context of cooperative OFDMA resource allocation [111], [112].

2.3.2 Iterative Approaches

As an alternative to game theory techniques, previous papers (such as [61]) have also investigated iterative algorithms for distributed multi-cell resource allocation. In these approaches, APs individually, and iteratively, make a decision on their transmit power and user scheduling, so as to optimize their contribution to the sum rate.

2.3.3 Algorithms for Cognitive Radio Networks

In the context of cellular networks as primary systems, some contributions propose to schedule the secondary traffic among frequency channels left unused or underutilized by the PUs, as in [113] and [114]. In particular, the system architecture proposed in [89] lets SUs belonging to a cognitive ad hoc network make opportunistic use of data channels left unused by a primary GSM (Global System Mobile) system. The proposed MAC protocol exploits the Request to Send (RTS) - Clear to Send (CTS) exchange and the Network Allocation Vector (NAV) concepts of the IEEE MAC protocol. Additionally, a commonly agreed, among SUs, control channel is used so that transmitter-receiver handshake is initiated through this channel. On the other hand, in [114] some mathematical approaches to describe the temporal behaviour of interfering signals obeying a lognormal shadowing distribution are presented, thus demonstrating that interference exhibits temporal fluctuations, which can be exploited by cognitive radios in an opportunistic manner.

In addition to that, other examples are available in the literature in the context of spectrum scheduling. An opportunistic frequency channel skipping protocol is proposed for search of better quality channel in [113], where the channel decision scheme is based on Signal-to-Noise Ratio (SNR). The key mechanism presented in [115] is that if the SNR is not favourable, mobile nodes can opportunistically schedule better quality frequency channels enabling data transmission at higher rates. Additionally, in order to consider the primary user activity, the number of spectrum handoff in a certain frequency band, is also used for spectrum decision in [116]. In [117], simple and distributed dynamic channel strategies are proposed and evaluated to select the best operating band which can maximize the total system performance, in the presence of multiple primary bands characterized by heterogeneous properties in terms of maximum data rate for secondary use and diverse traffic patterns.

Intelligent techniques have also been proposed for selecting the cognitive radios' frequency channels. The approach required to make optimal solutions in cognitive radio is multi-objective in nature; in fact, many different and competing objectives must be concurrently evaluated to determine a solution. For this reason, in [118] a genetic algorithm is presented to perform intelligent radio selection and adaptation, in terms of frequency channel, modulation scheme, etc. The objective in this framework is to maximize the defined objective function, depending on different parameters (*e.g.*, BER, SNIR, data rate, occupied bandwidth, spectral efficiency, computational complexity, transmission power). On the other hand, in [119] an opportunistic channel selection strategy is presented, which is based on new filtering and fuzzy based techniques for both channel estimation and channel selection, whereas in [120] an adaptive and distributed approach to spectrum allocation in mobile ad-hoc networks is presented. It is based on a local bargaining approach where users affected by the mobility event self-organize into bargaining groups, and adapt their spectrum assignment to approximate a new optimal assignment. Finally, game theoretic concepts have also been applied to investigate frequency channel selection, like in [121], [122], where the idea is to model the cognitive radios as different players, the controllable communication parameters as actions that can be performed by each of the players, and the SINRs of the SUs as players' utility functions in the game.

2.4 SoA related to Task 3: Scheduling Techniques for Heterogeneous Networks

Heterogeneous networks are designed to extend the coverage offered by the single wireless systems which compose it, increase spectral efficiency and provide service at higher quality and lower price, realizing flexibility at the expense of an increased complexity. In the literature, different degrees of integration have been presented:

– *open coupling*, according to which different and separate access and transport networks are present,
– *loose coupling*, according to which a link between the Authentication Authorization and Accounting (AAA) unit and the Home Location Register (HLR) allows a common authentication mechanism,
– *tight coupling*, according to which a certain network (*e.g.*, a WLAN) is connected to the core network of the cellular system which perceive it as part of itself.

As an example, 3GPP standardizes UTRAN and GERAN to operate in tight coupling mode, so that the core network supports information exchange between the RNCs of all Radio Access Networks (RANs) involved, thus allowing CRRM. This is responsible for dynamic and intelligent cooperation among different RANs, depending on static and dynamic measurements with the following objectives:

– coordination of different sets of resources controlled by the RRM functionalities in single systems,

– trunking gain, in order to reduce the block error probability in case of RT applications and to increase throughput while reducing delay for NRT applications, and to reduce block probability in handover procedure,
– QoS management;

these objectives can be achieved through two different architectures, which are also depicted in Figure 3:

– integrated CRRM, according to which functionalities are implemented in each single cell/AP in a coordinated way. In this case no new entities should be introduced;
– centralized CRRM, according to which a centralized node takes decision in an optimal way.

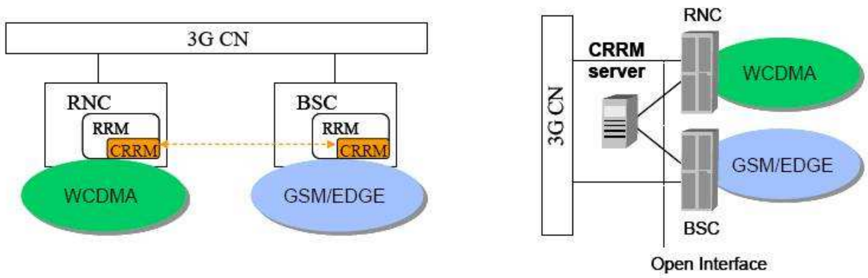

Figure 3: Integrated vs. Centralized CRRM Architecture

Despite the fact CRRM has been under investigation for years, there are still very few works about scheduling over different RANs, as [123]. This happens because a very tight implementation of CRRM is required, and several issues should be addressed, such as traffic division over different systems and the relevant packet synchronization and jitter control.

The dynamics of handover between two coexisting wireless standards and the consequent exploitation of the offered diversity by the use of multi-standard terminals will be investigated. The potential capacity benefits of mobile-initiated vertical handovers are substantial. However, it is important to choose the correct VHO criteria in order to achieve optimum load balancing and (global and social) equilibrium states.

As a result of the massive deployment of coexisting wireless networks, mobile users often have several choices of collocated WLANs to connect to. This situation is exacerbated by the deployment of large scale mobile third-generation systems operated by major network operators, as well as other, smaller unregulated networks. In fact, mobile user chips already exist which support multiple standards and, additionally, there has been a significant amount of work in creating flexible radio devices capable of connecting to *any* existing standard [124]. It is therefore reasonable to expect that, in the near future, users will have the option to connect to different networks and to switch dynamically between them on a real-time basis, based on the offered throughput and/or price.

The dynamics of this process has several interesting aspects. Firstly, due to the lack of a central controlling authority, mobile users become selfish and, even though users now have more choices, they still need to compete for the finite resources of nearby APs. Moreover, the repeated structure of the process makes users rely on past information available to them, in order to learn to adapt to the environment. To make things worse, since only local information about the past states of the system may be available (*e.g.*, the average service throughput per user), it is not clear how users may use this information in an effective manner. This process can be modelled in terms of a non-cooperative game. There have been two different directions of similar past work on this problem. To begin with, there has been a significant body of work on applications of game theory to wireless networks [57]. For example, uncoordinated random access channels have been analyzed by optimizing their transmission probabilities [125], or their power control [126]. Another application is in CDMA systems, as shown in [127] – [129]. More specifically, in the direction of connecting to multiple wireless nodes, [130] considered the possibility of connecting to several 802.11 APs using a single WLAN card.

3 DISCUSSION ON TOOLS AND METHODS TO DESIGN SCHEDULING AND ADAPTIVE RADIO RESOURCE ASSIGNMENT ALGORITHMS

The aim of this Section is to define proper tools and methods to design new scheduling and radio resource assignment algorithms. The way pursued to achieve the objective is an accurate analysis of the algorithms surveyed in the previous Section. In particular, according to the specific Task they addressed (*i.e.*, multi-carrier and spatial division based systems, distributed networks, heterogeneous networks) for each algorithm an analysis of the inputs required (*e.g.*, channel quality estimation, application type, etc.), the types of system which they apply to (in case more network types can be supported), the type of approach implemented in designing them (*e.g.*, heuristic, mathematical formulation, cross-layer based, etc.), is performed.

Before proceeding with the analysis and defining tools and methods for future algorithms design, it is fundamental, for sake of precision, to clarify their definitions and the relevant implications. In Figure 4 a graphical representation of the interaction between scheduling, tool, and method concepts is drawn. Taking into account that an algorithm is *a sequence of instructions performed by a computer to complete a task*, as a first step it is necessary to define the set of outputs expected, and which objective should be pursued. Clearly, for a scheduling and resource allocation algorithm the list of outputs is composed of the users (flows) to be served and the relevant set of radio resources. This can be done in at least as many ways as the possible objectives are, for example throughput maximization, fairness guarantee, QoS management, etc.. According to the objective and the outputs required, a list of inputs should be provided and the most appropriate design method chosen. Finally, as a last step the most suitable tool, according to an opportune trade-off between complexity and precision, is selected. So, the main difference between methods and tools is that methods are analytical procedures used to pursue some objectives, whereas tools are instruments used to implement a certain strategy.

According to the abovementioned definitions, it can be noticed that for example the Maximum Sum Rate is not a real algorithm, but rather an algorithm objective, which can be pursued applying the optimization method, and can be implemented using different tools like for example linear programming or heuristics. However, sometimes it is really hard to find a separation between tool and method, like for example for game theory, which is a method to model distributed systems and also a mathematical tool to represent their behaviour. In the following we will refer to the strategies presented in the previous Section as “approaches”, regardless of the fact that they specifically represent methods, tools or real algorithms, because at least they can generate classes of algorithm.

So, in the following, the specific role (*i.e.*, tool, method or objective) will be clarified, when possible, for each approach presented in the previous Section. Besides this classification, the main advantages and drawbacks related to each approach will be emphasized, in order to identify which are the main potentialities and limitations and to finally indicate which should be the mandatory characteristics of an advanced scheduling strategy in order to cope with the challenging features of future wireless systems.

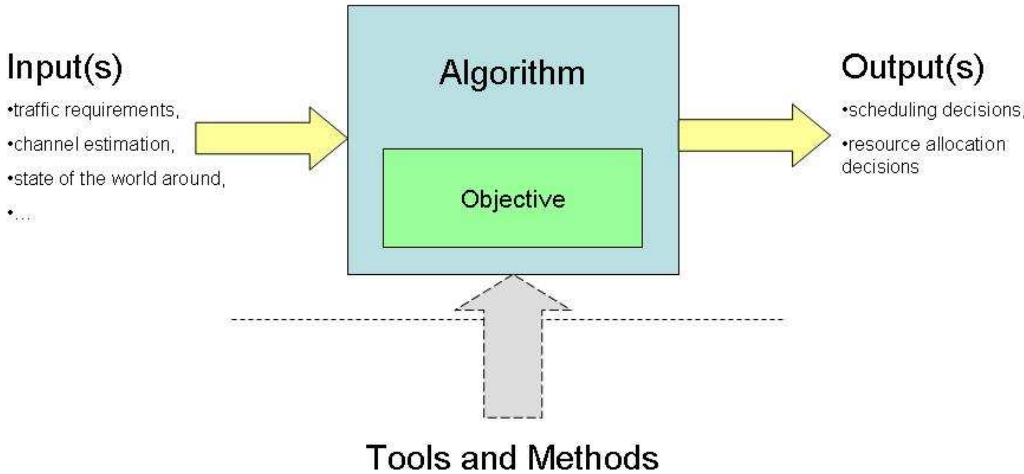

Figure 4: Graphical Representation of Algorithm Design and Behaviour

3.1 Analysis of the Tools and Methods Used in the Literature

Before defining what are the tools and methods most appropriate to design scheduling and resource allocation strategies, it could be useful to analyze those commonly used in the literature. To this aim the specific set of inputs, so as the main pros and cons of the approaches presented in Section 2 will be revised and emphasized.

The **Maximum Sum Rate** approach is mainly an objective pursued by a class of algorithms, which may differ usually on the tool used. As the name anticipates, the aim is maximizing the instantaneous sum rate supported by the system; hence the metric to be optimized is the sum capacity. In order to pursue this aim, the method used is optimization and the inputs required are the set of SINR perceived by each user, since they allow the calculation of the Shannon capacity. This metric can be easily computed by each user through the use of pilot signals and/or assuming that channel estimation can be performed according to previously received data. Moreover, it can be applied to any kind of wireless system. The tools usually used are greedy optimization and waterfilling power allocation. Clearly, this approach is channel-adaptive. Its main advantage is that it utilizes as much capacity as possible, which is very important in wireless system due to spectrum scarcity, and computational complexity is substantially low. However, MSR results in a starved worst-case user, which is especially not recommendable in cellular systems, where large path loss may occur and it is typical for several users to receive no resources at all for possibly long periods of time. So, the strategy could be terribly unfair. Hence, the MSR algorithm is viable only when all users have nearly identical channel conditions and a relatively large degree of latency is tolerable.

The **Minimum Transmit Power** approach is also mainly an objective pursued by a class of algorithms, which may differ on the tool used. In particular this approach is formulated as a linear programming problem and solved with standard LP tools. One of the advantages of this approach is that, by setting adequate rates for each user in the optimization problem, the system can provide each user with exactly the amount of resources requested with the minimum power necessary. However, as for the Maximum Sum Rate algorithm, the feasibility of this approach depends on the accuracy of the SINR measurements, and it is hardly feasible in fast fading environments. Moreover, the complexity of its implementation depends on the tool used for solving the LP problem: exact solutions are generally very complex to find, but there are simple heuristics that obtain results close to the optimum with a medium-low computational effort.

The **Maximum Fairness** approach is mainly an objective pursued by a class of algorithms, which may differ usually on the tool used. It has the aim of maximizing the instantaneous minimum rate supported by each user, a problem which is usually referred to as Max-Min. So, fairness guarantee is of primary concern for this algorithm. In order to pursue this aim, the method used is optimization and the inputs required are the set of SINR perceived by each user, which is used to select the worst user to be allocated with the maximum possible rate, in order to equalize transmission rates among different users. It can be applied to any kind of system. Clearly, also this strategy is channel-adaptive. The main advantage of such approach is that it achieves the best performance for the most under-served user, with a slight gain for optimal power allocation over its allocated subcarriers relative to an equal power allocation. However, the Maximum Fairness approach achieves complete fairness while sacrificing significant throughput, since it is limited by the user with the worst channel quality. Moreover, the rate distribution among users is not flexible and, as already mentioned in Section 2.1, in its ideal formulation, the tool used is the joint optimization of subcarrier allocation and power control, which is remarkably more complex than the implementation in MSR, due to the non concavity of the objective function, which leads to a NP-hard problem. Hence, it is appropriate only for fixed, equal rate applications.

The **Proportional Rate Constraints** approach is mainly an objective pursued by a class of algorithms, which may differ usually on the tool used. It has the aim of maximizing the instantaneous sum throughput, given the additional constraint that each user's data rate is proportional to a set of pre-determined system parameters which allow service differentiation. So, trade-off between throughput and fairness is the main objective of this strategy. In order to pursue this aim, the method used is optimization and the inputs required is the set of SINR perceived by each user and the set of parameters related to the specific application under consideration. It can be applied to any kind of system. Clearly, this strategy is channel-adaptive and someway application-adaptive. The main advantages of such approach are the following: throughput maximization is pursued also taking into account fairness guarantee; rate allocation flexibility can be achieved by varying the set of parameters related to the kind of application taken in consideration; some service differentiation is introduced, so a flexible trade-off between throughput and fairness is pursued. However, also this approach shows a high complexity when the tool used is the joint optimization of subcarrier allocation and power control due to the non convexity of the feasible set of variables and it may not always be possible to achieve the desired rate constraints in real-time. Hence, some simplified sub-optimal tools should be introduced.

The **Proportional Fairness** approach is mainly an objective pursued by a class of algorithms, which may differ usually on the tool used. It has the aim of maximizing the sum rate supported by the system while guaranteeing long term fairness among users. In this case, the method used is not optimization, but a simple comparison among previously computed ratios. In order to pursue this aim, the inputs required is the set of SINR perceived by each user and the mean rate required by each user. Although Proportional Fairness scheduling was originally designed for a single channel time-slotted system, it can be adapted to an OFDMA system. Clearly, this approach is channel-adaptive. The main advantages of such approach are the following: Proportional Fairness approaches the throughput of the MSR but with an expected penalty due to its support for under-served users; it is fairly simple to implement; it achieves a practical balance between throughput and fairness; it introduces some flexibility through the long term requirement. However, a third element enters the trade-off, which is latency, which may seriously affect real time users.

Game Theory is not an algorithm but rather a theoretical framework whose aim is providing a fully distributed approach to the resource allocation problem. In order to pursue this aim, each user tries to maximize his own utility function, which is basically related to the capacity. This approach can be suited to each kind of air interface as long as the network architecture is distributed. Moreover, it is commonly implemented in a channel-adaptive way. The main advantage of such approach is that it perfectly applies to infrastructure-less networks, such as ad hoc networks, since each user takes decision autonomously, and may also possibly be applied to cognitive radio. However, Game Theory approaches do not guarantee neither maximization of throughput nor optimal distribution of resources, since each user tries to get as many resources as possible selfishly, which is not a good policy from a network point of view, whose objective is trying to serve as many users as possible according to at least their minimum performance requirement. Moreover, the game theoretic framework is a quite complex mathematical tool. For this reason, it could be mainly used as a good benchmark of how a set of nodes behaves in a network without centralized control.

Genetic-based approaches are a class of algorithms whose aim is maximizing an objective function suitably defined, which depends on different parameters. In order to pursue this aim, the method used is optimization of multi-objective functions. This approach can be implemented in any kind of system with a set of requirements. Moreover, it can be applied in a distributed network and in cognitive radio. Clearly, also this approach is channel-adaptive. Its main advantage is that it can pursue different objectives simultaneously and can be implemented in a distributed way. However, a multi-objective optimization problem may require high complexity tools, and the distributed approach leads to suboptimal resource utilization.

A common framework for part of them (*i.e.*, Maximum Sum Rate, Maximum Fairness, Proportional Rate and Proportional Fairness) is dual optimization techniques. Dual methods work well in OFDMA problems due to the problem structure, since there are typically a lot more subcarriers K than users M. In most OFDMA/MC resource allocation problems, the objective function is separable across the K subcarriers, and the number of constraints is in the order of the number of users M. This makes dual optimization techniques an ideal approach to solving them, since the duality gap is typically quite small in these types of problems. Additionally, the solution to the dual problem involves very simple closed-form power, subcarrier, and rate allocation functions for both continuous and discrete rates, thus, further enhancing the attractiveness of using a dual approach. In Table 1, a synthetic comparison of the strategies presented above is reported.

Approach / **Feature**	Maximum Sum Rate	Minimum Transmit Power	Maximum Fairness	Proportional Rate Constraints	Proportional Fair	Game Theory	Genetic-based
Channel Adaptiveness	YES	YES	YES	YES	YES	YES	YES
Tool Used	max sum capacity optimization	linear programming	max-min problem optimization	max of sum throughput with additional constraints	selection of the user with highest istant. rate over average rate	game theory	multi-objective functions
List of Inputs	$SINR_i$	$SINR_i$, average rates	$SINR_i$	$SINR_i$, user weights	$SINR_i$, average rates	$SINR_i$, other introducible	$SINR_i$, other introducible
Fairness Guarantee	NO	YES	YES	YES	YES	NO	NO
Aim	sum rate maximization	transmit power minimization	fairness maximization	fairness / sum rate trade-off	fairness / sum rate trade-off	each user maximizes his own utility function	each user maximizes his own multi-objective function
Complexity	low	high	high	high	low	high	high
Service Differentiation	NO	possible	NO	YES	NO	possible	possible
References	[53], [54]	[100], [101]	[102], [103]	[103]-[105]	[31], [32]	[107]-[112]	[92], [118]

Table 1: Synthetic Comparison among the Approaches Presented

3.2 Discussion on Tools and Methods to Design Future Scheduling and Radio Resource Assignment Algorithms

The preceding analysis of the main algorithms in the literature, the relevant types of inputs and approaches used in order to design them, the types of system which they apply to, can be used to discuss which should be the main characteristics and properties of future algorithms. The definition of the JRAs to be carried out within this WP will be carried out trying to include as many of these indications as possible, according to the specific topics of interest for the partners.

From the analysis of the literature (and some intuitive considerations), it is clear that a mandatory characteristic that a scheduling algorithm should have, whatever is the underlying system, is the adaptiveness to channel variations. In fact, in wireless systems it is fundamental to use spectrum at the best of its conditions, in order to fully exploit multiuser diversity, and not to waste a resource which is scarce by nature. However, one of the issues still to be addressed is which kind of metric should be used to estimate channel quality. For example, SINR can be used when channel has no selective effects, vice versa a vector of channel parameters could be preferable if the channel is frequency-selective, or the air interface is multi-antenna. The frequency of updating of this metric should be related to channel variations speed and to the algorithm requirements, since it may take decisions according to instantaneous or averaged channel conditions. This should be not confused with application metrics which are related to perceived quality, and are different for voice or web browsing or others applications. In fact, when user-centric applications are under consideration (*i.e.*, voice or video transmission), an average over some milliseconds of the perceived SINR could be considered as a satisfactory metric, since humans are insensitive to variations occurring at a frequency higher than a few Hz. However, when application is data-centric (*e.g.*, FTP, web browsing, etc.), an average of the SINR is not a satisfactory metric any longer, but rather the focus should be shifted toward a maximum block error rate to be guaranteed, which in case of violation would lead to loss of data. Moreover, it should be considered that future systems promise to provide high bit rates also at high user speed. Since large speeds imply shorter correlation in channel behaviour, channel estimation can be less reliable. In this case faster channel prediction/estimation/tracking schemes could be investigated to ensure the best possible match between the Channel Quality Indicator (CQI) level and the true channel conditions that the mobile experiences when being assigned the respective AMC combination. So, when designing scheduling algorithms, appropriate CQIs should be identified, possibly considering not only estimation based on observation of the past, but also considering channel prediction models.

As shown in Table 1, the main approaches published in the literature are based on methods such as optimization, and implement tools such as game theory or genetic formulation. These have the merit of providing an elegant formalization of the problem and sometimes an upper bound (as for the MSR) or a good benchmark of possibly realistic behaviours of a network under certain conditions (as for the game theory). However, they have not been proved yet to be really suited to modern wireless networks, where service differentiation should be guaranteed. In fact, different quality specifications can result in different requirements to be considered in the scheduling policy, and in different behaviour of the nodes inside the network. For this reason, it seems that optimization, game theory, multi-objective functions, are not the best solutions due to the high complexity and the relevant high computational time and cost. So, simulative tools are recommendable to test realistic network performance, and algorithm design should be based on heuristic methods which allow the introduction of parameters able to tackle also the required service differentiation. In fact, despite frameworks such as optimization can cope with service differentiation through the use, for example, of multi-objective functions (as done in genetic-based algorithms), it is evident that as the number of parameters needed to describe the system increases (to include the aggregation of different services, traffic models, user profiles and mobility patterns), in the same way the mathematical complexity of the scheduling and resource allocation optimization problem increases, leading to processing complexity and delay that can be unacceptably high, especially considering that future systems are supposed to take scheduling decisions in time of the order of (very) few milliseconds (*e.g.*, 2 ms in HPSA and 5 ms in WiMAX). Therefore, it is clear that complexity is also an issue of primary concern in such networks. So, the main problem related to the choice between convex optimization algorithms or heuristic algorithms is the complexity/speed trade-off. Simplified suboptimal algorithms may compete with heuristic algorithms. However optimal solutions are still useful as a benchmark. Moreover, fuzzy logic is good at decision making for complex process, thus, it should be considered also as a tool to incorporate heuristics.

The emphasis on simulative tests and on the use of heuristics as tools in algorithm design does not mean that analytical approaches and mathematical frameworks are out of the scope of this WP. On the contrary, they keep all their relevance to identify benchmarks and possible bounds, as for example shown in works like [16] or in [59], where a general mathematical framework is presented for PHY-MAC cross-layer design. Nevertheless, game theory is still a good method to evaluate the behaviour of a distributed system. Moreover, they still have a great potential in specific scenarios. In fact, while cellular systems are devoted to a human end user willing to access many kinds of services, emerging ad hoc and mesh network paradigms can be deployed with a completely different aim. Just as an example, it could be considered an emergency scenario, where sensor nodes are deployed over a certain area to be monitored. These sensing nodes are sometimes triggered to send data to collector nodes which, in turn, relay them to a control unit, which takes decision consequently. In such a peculiar scenario, there is no service differentiation and only one, very specific, application is supported. So, completely different challenges should be faced by algorithm designers, such as the application-specific requirement, and mathematical tools could be well suited to face the new problem.

Another interesting method to design scheduling and resource assignment techniques could be Markov chains. In particular they could be used to model the system variations due to the behaviour of traffic sources. In fact, this method has been already used in addressing the scheduling problem to model the state transitions occurring in the wireless channel [40], but have been abandoned as proved to be not satisfactory [41]. However, some interesting works showed that they are a very effective method to model traffic behaviour in random access based systems [132]. So, the application of this method to the scheduling context is still largely to be tested.

As previously mentioned, one of the big issues that algorithm designers should face is QoS management. This set of constraints, though indicated as a crucial topic already for some years, is still far away from being sufficiently addressed in the literature, both in the case of multi-service networks and of ad hoc applications. This means that a preliminary work should be performed towards the identification of synthetic parameters able to tackle the (possibly) different requirements set by each specific application, both in form of inputs data and as parameters to be adjusted in the algorithm, such as message structure, upper layer protocol behaviour, source coding/encoding behaviour. This is expected to be also performed including the cross-layer approach as a feature in the design of new scheduling algorithms and, hence, the possibility of information exchange even between non adjacent layers of the protocol stack, since its potential is still largely unknown. An example of its use can be provided by analyzing what are the appropriate inputs to consider for an algorithm in charge of scheduling traffic among heterogeneous networks. First of all, this algorithm should take into account physical layer information such as Received Signal Strenght (RSS) and data link layer information such as resource utilization, load and congestion control. Additionally, packet and network level aspects such as delay, jitter and loss statistics as well as the evaluation of achievable throughput in every network, should be considered. Finally, it is worth mentioning that the decision about the best network where to schedule the user traffic does not only involve technical aspects, but also application layer inputs not necessarily related to QoS perception, such as user preferences, user perception of the trade-off QoS versus cost, battery lifetime of the portable devices, etc.. This feature suggests a strong interaction with other WPs, from which precious inputs could arrive to pursue the main objective of this WP.

Another interesting further direction is interference awareness. In fact, as discussed in previous Sections, due to the high reuse of spectrum, current and future wireless systems are interference-limited. Most of the works on scheduling still handle only the problem of channel awareness as fading awareness, whereas channel capacity and, hence, bit rates, are highly affected by the interference perceived. A traditional approach to manage interference is power control. However, since it is usually implemented as a “last minute” solution, often there is no possibility to exploit some interference prediction, since power levels can be retuned at timing shorter than the scheduling interval. Moreover, the always increasing reduction of scheduling time (*e.g.*, 2 ms in HSDPA) has a highly dangerous potential from the point of view of interference, since in a very few ms the number of users allocated (and all the relevant parameters) can change many times, leading to the complete impossibility to manage interference in any way. A possible solution could be finding some methods to “plan” interference in a network. In fact, it is clear that the potentialities of including some tools to predict and prevent it, not only through the use of power control but rather to a careful resource allocation policy, are still an open issue.

As a final remark, an important issue is fairness. First of all, it should be discussed if the conventional definition of fairness still holds in modern and future wireless networks. In fact, in the presence of many different applications, each one characterized by its own requirements (in terms of average bit rate, delay, bit error rate, or application-specific metrics) it is clear that the concept of fairness as intended nowadays is actually outdated: each user is not interested in how much it is served with respect to other users, but rather with respect to its own specific requirements. This introduces a new concept of fairness, which could be defined in a “reflexive” way: each flow/node/user would like to compute the level of fairness it perceives with respect to its expectation (both in the sense of “hope” and “average”). In this sense fairness is still an issue, and needs to be investigated starting from a different, innovative point of view.

4. INTENDED CONTRIBUTIONS

In this Section the contributions declared by the partners to WPR.8 activities are provided in terms of JRAs. In particular, for each of them the list of participants and the relevant backgrounds, the responsible, a detailed description with a tentative schedule and the expected outcomes are reported. Finally, for each partner the specific role will be given according to the following classification: P1 is the JRA leader, P2 is the second participant who helps P1 in JRA coordination, P3 supports P1 and P2 providing suggestion, material and feedback, and finally P4 acts as an internal reviewer.

4.1 JRA1a: Scheduling techniques for Multi-Carrier and Space Division Systems

Participants: UPC (P1), CTTC (P2), CNIT-FE (P3)

Leader: UPC

Responsible: Ana Pérez-Neira

4.1.1 JRA Objectives

Next generation broadband wireless standards use OFDMA as the preferred physical layer multiple access scheme, especially for downlink. Due to the limited resources available at the base station, as for bandwidth and power, multiple antennas (SDMA) and intelligent allocation of these resources to the users is crucial for delivering the best possible QoS to the consumer with the least cost. In order to manage all the degrees of freedom, this JRA contemplates different strategies: optimization of time-averaged or instantaneous PHY or MAC costs and constraints, convex optimization or sub-optimal heuristic algorithms, adaptive algorithms based on stochastic approximation techniques. Also, algorithms assuming perfect, imperfect and partial CSI, like opportunistic schemes, will be considered. During the lifetime of this JRA, and depending on the interactions among researchers, more stress will be given on one point or another. Of main importance because of its simplicity and practical interest they will be opportunistic schemes, convex optimization and cross-layer scheduling.

4.1.2 Background of Institutions / Researchers Involved

4.1.2.1 UPC

The “Array and Multichannel Signal Processing Group”, of the “Signal Theory and Communications Department” of UPC, carries out its research activities in relation with physical layer of communication systems aspects under different diversity schemes, in order to cope with several problems in single-user and multiuser communication networks. The activities of the group also take into account the data link and the network layers in those aspects related with the physical layer. More concisely, recent projects on PHY-MAC cross-layer are:

– ESA Study “Application of MIMO to satellite communications,”: in this project one of the tasks was devoted to the study of spatial scheduling for broadcast satellite DVB-S2;
– MIMOWA, “MIMO for Wireless Access” (Medea+ project): application of the previous topics to real 4G standards (IEEE 802.11n, WiMAX, etc.), and collaboration in the development of testbeds for such standards;
– GIRAFA, “Intelligent radio resource management for wireless ad-hoc networks by jeans of: advanced signal processing and fuzzy logic”.

A complete list of projects and publications, in addition to other teaching activities of the group, can be found in the web page http://gps-tsc.upc.es/array. The person in charge of this JRA, namely A. Pérez-Neira, has carried out for the past eight years research on cross-layer scheduling with the main focus on spatial diversity and OFDM systems. She has ten Journal papers on the topic, one special issue and more than twenty conference papers.

4.1.2.2 CTTC

CTTC, and the person involved in this JRA, namely L. Giupponi, has strong background in Space Division systems, especially gained during the realization of different research projects, such as the ESA funded MIMO-SAT project, and the MIMOWA project. Besides, CTTC has great experience in technological implementation of MIMO technology, as demonstrated by the availability in its lab of the GEDIMIS testbed, devoted to proof of concepts of Space Division systems.

4.1.2.3 CNIT-FE

The members of the Telecommunication group at the University of Ferrara (CNIT-FE) involved in this JRA have research interests and expertise covering different aspects of the wireless communications related to resource allocation and scheduling, adaptive modulation and coding, multi-carrier and multiple antenna systems. In the last years they gained expertise on techniques for adaptive resource allocation in multi-user multi-antenna system in the presence of interference, in cross-layer design of scheduling algorithms with heterogeneous traffic sources including video, in performance and design of adaptive modulation systems. The CNIT-FE member mainly involved in this activity, namely V. Tralli, has a solid background in the area of RRM and scheduling. He has been active on this subject in the NoE NEWCOM, doing joint research for MC-CDMA systems, and in the framework of industrial projects. He is also active in the EU-Project OPTIMIX on optimization of multimedia over wireless via cross-layer design.

4.1.3 Description of Activities to be Performed

In order to design efficient MIMO-OFDMA algorithms, this task focuses mainly on: i) cross-layer spectral efficiency, because it offers more realistic results than information-theoretic capacity; ii) convex optimization, because of the use of dual methods in OFDMA problems; iii) agile and low complexity opportunistic schemes. Some of the scenarios of interest are future mobile standards, low energy applications and cognitive transceivers, where spatial sharing is a new issue to be explored:

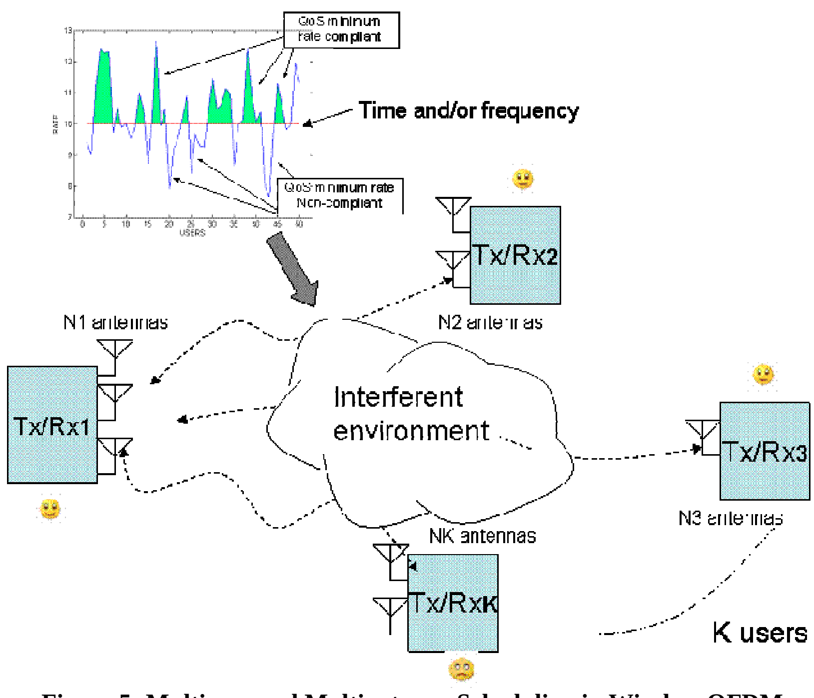

Figure 5: Multiuser and Multiantenna Scheduling in Wireless OFDM

– *opportunistic transmission and spectrum access:* in multiuser systems, opportunistic transmission has been proved to be the strategy that optimizes capacity in many situations whenever channel state information is available at the transmitter (*e.g.*, in multibeam transmission when a big amount of users want to access the system, in multi-carrier transmission when the available transmitting power is low). Not only due to this fact but also due to its low complexity, actually, opportunistic systems are the only multiuser transmission techniques that are adopted in the current standards. This strategy decides when to transmit, to which user(s) and the amount of power to allocate among them. The performance gain of opportunistic communications comes from exploiting the fluctuations of the channel of one or more than one user (*e.g.*, multiuser diversity), and new scenarios and/or QoS requirements ask in the near future for further study the opportunistic strategy in order to incorporate:

- the impact of QoS on multiuser diversity and how the QoS diversity that arises in heterogeneous networks impact on the user selection; because of the nature of the wireless channel, most of the time QoS constraints will be formulated as outage or availability;
- autonomic and Opportunistic Spectrum Access (OSA): opportunistic strategies facilitate decision making, thus, being very appropriate to build up context aware systems. Decision theory and its different criteria (*e.g.*, expected value, maximax, maximin or minimax) should be taken into account to facilitate the resource management. Work on how decision theory and information theory relate in order to achieve the channel capacity is to be done. For instance, note that the Region Of Convergence (ROC), where the addition of the probability of false alarm and probability of detection is a constant, can be related to the capacity region. Finally, depending on the uncertainty and complexity of the context, some degree of fuzziness and complexity of the decision variables can help to solve the decision or resource management problem;
- in Opportunistic MultiBeamforming (OMB) interference can be predicted, thus helping in the interference management. As OMB works in the angular domain, studies on aerial entropy and modulation diversity will be considered.

4.1.4 Tools Used to Achieve the JRA Objectives

UPC will cooperate with CTTC and other partners of the JRA1b, especially with CNIT-FE on guaranteeing QoS to different users/applications, implementing a cross-layer approach, in order to perform the control of interference in scenarios with multiple access point, while considering adaptive modulation in the system. Initially, related reference papers/books will be shared. In parallel, there will be an exchange of ideas regarding the simulation models that each partner has or plans to implement for the assessment of the investigated algorithms. Specifically, the activities in SDMA scheduling in JRA1a will be carried out in parallel with those in OFDM-SISO scheduling in JRA1b, exchanging ideas on possible issues that need to be investigated and combined in both topics.

4.1.5 Links to Other NEWCOM++ WPRs

This JRA1a will interact mainly with WPR2. This WP explores the role of feedback in two-way wireless communication networks and its relation to the capability of resolving the time-varying channel state. Inputs will be provided on:

- information-theoretic understanding of the impact of non-ideal CSI in feedback-based systems,
- performance measures under channel uncertainty,
- tight outer-bounds on information rates as a function of channel variation and reciprocity,
- feedback-based precoding strategies for downlink transmission.

4.1.6 Expected Outcomes

The following list includes a number of possible expected JRA outcomes:

- joint papers,
- short and medium term missions,
- joint PhD supervisions,
- joint organization of workshops,
- joint contributions to spreading of excellence and integration WPs.

4.1.7 Schedule of Activities

The following preliminary schedule covers the sub-activity milestones from T0+4 till T0+22.

T0+3: Official start of the activities.

T0+4: Initial interactions among partners, sub-activity definitions, contributions to DR8.1.

T0+8: SoA/Literature Study – Initial planning among partners for common simulation scenarios and possible integration activities and exchanges. Define the collaboration means between JRA1a and JRA1b.

T0+12: Start of the second phase of activities. Implementation of possible integration tools: 3-month exchange and/or remote collaboration. Possible outcomes: joint conference papers.

T0+16: End of the second phase of joint activities and start of the third phase. Possible integration tools: 3-month exchange. Possible outcomes: joint journal paper(s), workshops or journal special issue preparation.

T0+20: End of the third phase of joint activities and start of the fourth phase. Possible integration tools: 3-month exchange and/or remote collaboration. Possible outcomes: joint journal paper(s), contribution to a joint workshop. Plan of contributions to DR8.2.

T0+22: End of the fourth phase and of the whole JRA. Possible integration tools: remote collaboration. Possible outcomes: joint journal paper(s). Contribution to DR8.2.

4.2 JRA1b: Scheduling Techniques for Multi-Carrier Systems

Participants: NKUA/IASA (P1), CNIT-PI (P2), UCL (P3), CNIT-FE (P4)

Leader: NKUA/IASA

Responsible: Nikos Dimitriou

4.2.1 JRA Objectives

This activity will focus on studying effective scheduling algorithms for OFDMA systems, such as WiMAX and LTE, which will incorporate the following degrees of freedom in a time-variant multipath broadband channel:

– sub-carriers and time slot (since TDMA is also considered);
– rate per subcarrier and, thus, bit loading;
– power per subcarrier.

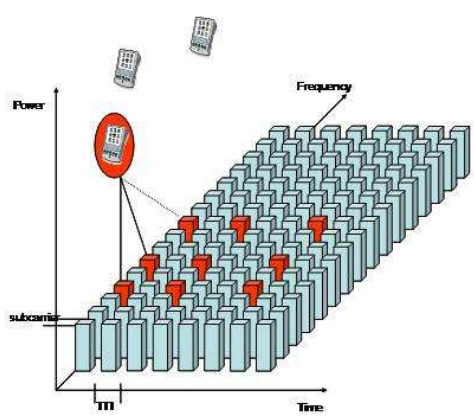

Figure 6: A Scheme of the Allocation Problem over OFDMA

4.2.2 Background of Institutions / Researchers Involved

4.2.2.1 NKUA/IASA

All NKUA/IASA group members that will be involved in this activity, namely N. Dimitriou, A. Moustakas, S. Stefanatos, P. Mertikopoulos, have a solid background in the areas of RRM and scheduling algorithms through participation to the following EU- projects:

- URANUS: in this project the focus of a specific sub-activity is on proposing algorithms for dynamically scheduling users among different air interfaces with the problem of vertical handover between wireless service providers;
- ESA Study "Study of the satellite role in 4G systems": in this project the focus of a specific sub-activity is on proposing access layer algorithms for allocating users over different time and frequency resources, for satellite systems that have multiple access schemes similar with LTE and WiMAX;
- NEWCOM Project C "Functional Design Aspects for Future Wireless Systems": in this project the focus was on deriving common performance metrics for the investigation of cross-layer adaptiveness in heterogeneous wireless networks.

4.2.2.2 UCL

UCL is the largest university in the French speaking area of Belgium. Its communications and remote sensing lab is active in the field of wireline and wireless communications systems. Baseband signal processing is the main activity with emphasis on equalization, joint detection, synchronization and radio resource management for OFDM, CDMA and combination thereof, in the context of UMTS LTE, xDSL and WiMAX systems. The UCL member that is involved in this activity, namely F. Brah, has a solid background in the areas of RRM. He participated in the CELTIC WISQUAS project. During this project, he developed resource allocation methods and algorithms for OFDM and OFDM-CDM systems with extension to MIMO-OFDM-CDM.

4.2.2.3 CNIT-PI

The people at CNIT-PI involved on this JRA, namely M. Moretti and G. Dainelli, have been active on the subject of resource allocation in OFDMA networks for a couple of years as witnessed by journal and conference publications. Their activity in this field is mainly focused on adaptive channel resource allocation and scheduling in multi-cellular environments with frequency reuse equal to one. For example, in [133], within the PRIMO project, it was proposed a modular cross-layer scheduler and resource allocator for a single-cell OFDMA system with the goals of achieving high spectral efficiency and long-term fairness among flows. Pursuing margin and rate adaptive approaches, this research unity has studied the conditions of convergence of various allocation algorithms. To achieve a feasible system with full frequency reuse, CNIT-PI has investigated various scenarios starting from totally centralized networks to fully distributed topologies. The activity in this field has spawned research collaboration with several academic institutions as well as private companies such as NTT DoCoMo and Telecom Italia Lab.

4.2.2.4 CNIT-FE

The members of the Telecommunication group at the University of Ferrara (CNIT-FE) involved in this JRA have research interests and expertise covering different aspects of the wireless communications related to resource allocation and scheduling, adaptive modulation and coding, multi-carrier and multiple antenna systems, as already described for the previous JRA.

4.2.3 Description of Activities to be Performed

Both LTE and WiMAX employ OFDMA as their main multiple access mechanism (although other options are also defined in the standards). The basic idea of OFDMA is to divide the available time-frequency space into a number of orthogonal subcarriers, of finite time and frequency support, each of which is assigned to a specific user. The assignment is performed by a scheduling algorithm implemented at the based station (access point). OFDMA provides a simple (albeit suboptimal) way of exploiting the channel's available degrees of freedom, both in time and frequency. In general, the scheduling algorithm may exploit all, or part, of the following available degrees of freedom for user allocation:

– time,
– frequency,
– power,
– rate.

It is noted that the active users themselves can also be viewed as an extra degree of freedom, in the sense that the scheduler may optimally assign part of them based on some optimality criterion.

For serving users with same QoS, traditional scheduling approaches divide the available signalling space into equal parts, assigning each of them to a single user. This intuitive approach can also be viewed as achieving fairness among users since the channel resources are equally shared. However, the drawback of this approach is that it is channel-blind: resources will be provided to a certain user irrespective of its channel conditions. In the case of a user experiencing severe fading (typical case in wireless communications), the transmitted signal will be lost with high probability, which translates to an inefficient use of the system's resources. If the scheduler had information on the user's channel state, it could modify (reduce) its transmitted rate to match the channel's conditions. Another option, would be to defer service to this user, due to poor channel conditions, and possibly transmit to another user which happens to have a better channel. Of course, the last option requires knowledge of channel state for all (or part) of the active users.

Clearly, knowledge of CSI can only help the scheduler in better utilization of the channel, which has led to an intensive research on this category of algorithms, usually named as channel-aware schedulers, due to the performance gains that provide compared to the non-channel-aware approached. Recognizing the potential of channel-aware scheduling, both LTE and WiMAX propel its employment, although explicit algorithms are not included in their description.

Essential for the success of any channel-aware scheduling algorithm is the (good) knowledge of each user's channel. The obvious approach for obtaining a channel estimate is each user transmitting his/her CSI periodically by mean of a channel CQI message. For low mobility, this sort of messaging has negligible impact on the system's throughput (although it is noted that in the case under consideration the CQI is not a single SNR value, but rather a vector of SNR values over the available bandwidth). Another possibility for obtaining CSI is to exploit the channel's reciprocity by systems operating in a TDD mode. In that case the base station can measure (estimate) the user's reverse-link channel, and this estimate can be employed as the user's forward link channel estimate. Higher mobility requires more frequent updating of the CSI and therefore may have impact on the system's throughput, due to increased overhead. In addition, feedback delays may have an impact on the scheduler's performance due to mismatch between the current channel state and its estimate employed by the scheduler.

Another important parameter of time-frequency channel-aware scheduling is the minimum resource allocation (RA) block. The optimal RA block from an information-theoretic perspective is a single sub-carrier. Unfortunately, the large number of subcarriers and number of users served by the base station makes scheduling algorithms operating under this RA block impractical. For this reason the minimum RA blocks adopted by the standards are named sub-channels, that consist of a number of sub-carriers for the duration of a few OFDM(A) symbols. When the sub-carriers are closely packed and contained within the channel's coherence bandwidth, there is no much loss in optimality. However, the standards also define sub-channels composed of sub-carriers far apart from each other (*e.g.*, PUSC sub-channel in WiMAX), for the case when no channel information is available. Employing a channel-aware scheduling algorithm with this type of RA blocks is certainly feasible, but will lead to a certain performance loss.

Many resource allocation algorithms have been proposed to take advantage of both the frequency selective nature of the channel and the multiuser diversity of OFDMA systems. Most of the works in the literature follow either the *margin* adaptive approach, formulating dynamic resource allocation with the goal of minimizing the transmitted power with a rate constraint for each user, or the *rate* adaptive approach aiming at maximizing the overall rate subject to a power constraint. Following these two approaches, energetic constraints can be coupled to traffic requirements in a cross-layer synthesis. Nonetheless, achieving traffic fairness and efficiency are two conflicting goals: the optimization of the radio resource utilization tends to penalize terminals with less performing channels, independently of their traffic level performance. Thus, the real point is to find a good, adaptive trade-off between these two adaptation capabilities.

According to the main strategies published, a preliminary taxonomy of the different scheduling algorithms could be the following:

(1) Fixed Scheduling Algorithms:

- non-channel-aware (*i.e.*, with fixed resource allocation):
  - round-robin user assignment,
  - constant power-rate-subcarrier allocation;

(2) Channel-based Scheduling Algorithms:

- channel-aware scheduling with ideal CSI knowledge:
  - optimal power-rate-sub-carrier allocation for each user based on specific performance criteria depending on the current channel state,
  - trade-off between sum-rate and fairness,
  - sub-optimal scheduling, *e.g.*, consideration of only sub-carrier and rate allocation keeping power fixed, solutions with low feedback or CSI complexity etc.;
- channel-aware scheduling with imperfect CSI:
  - delayed feedback resulting in outdated CSI,
  - errors introduced also from non-ideal channel estimation,
  - statistical modelling of CSI errors allowing optimal scheduling.

The following issues will be subject to investigation during the activity:

- constrained resource allocation strategies and algorithms,
- joint power and subchannels allocation,
- power, fairness and minimum rate constraints,
- allocation based on imperfect CSI,
- feedback reduction issues,
- subcarrier allocation per user (*e.g.*, individual SCs/user, sub-band/user (AMC),
- rate allocation per subcarrier,
- power allocation per subcarrier.

4.2.4 Tools Used to Achieve the JRA Objectives

The focus in the beginning will be on sharing related reference papers/books that contain algorithms and other useful information for the topic of interest. In parallel, there will be an exchange of ideas regarding the simulation models that each partner has or plans to implement for the assessment of the investigated algorithms. This will also include a simulation calibration procedure, in order to ensure the coherence of the simulation results contributed by different partners. Additionally, there will be an effort to have a common description method for the simulation models used in different places, in order for them to be easily exchanged among partners. In case all partners agree, another option is to develop a common MATLAB WiMAX platform to simulate the scheduling algorithms to evaluate. The goal is to have a common environment to compare the performance of the different proposals.

Regarding the researchers mobility, this will be organized as soon as there has been a preparatory joint effort in the first phase of literature review and definition of specific scenarios/goals. At that point, specific researcher short visits could be planned, in order to implement parts of the activity, which could lead to either joint papers, or joint simulation campaigns or joint working groups. Nevertheless, CNIT-PI and NKUA/IASA are willing to host at least one exchange visit for 3/6/12 months.

4.2.5 Links to Other NEWCOM++ WPRs

Since the OFDMA systems under discussion will have to implement adaptive modulation and coding, it is expected that there will be an interaction between WPR.8 and WPR.3, especially in terms of modelling the AMC throughput vs. SNR mapping in system-level simulations.

4.2.6 Expected Outcomes

The following list includes a number of possible expected JRA outcomes. A more precise list will be decided after the preparatory phase (T0+8):

- common software modules,
- joint papers,
- short and medium term missions,
- joint PhD supervisions,
- joint tutorials,
- organization of courses, special issues,
- joint contributions to spreading of excellence and integration WPs.

4.2.7 Schedule of Activities

The following preliminary schedule covers the sub-activity milestones from T0+4 till T0+22.

T0+3: Official start of the activities.

T0+4: Initial interactions among partners, sub-activity definitions, contributions to DR8.1.

T0+8: SoA/Literature Study – Initial planning among partners for common simulation scenarios and possible integration activities and exchanges. Planning of possible synergies with JRA1a.

T0+12: Start of the second phase of activities. Implementation of possible integration tools: 3-month exchange and/or remote collaboration. Possible outcomes: joint conference papers.

T0+16: End of the second phase of joint activities and start of the third phase. Possible integration tools: 3-month exchange. Possible outcomes: joint journal paper(s), journal special issue preparation.

T0+20: End of the third phase of joint activities and start of the fourth phase. Possible integration tools: 3-month exchange and/or remote collaboration. Possible outcomes: joint journal paper(s). Plan of contributions to DR8.2.

T0+22: End of the fourth phase and of the whole JRA. Possible integration tools: remote collaboration. Possible outcomes: joint journal paper(s). Contribution to a joint workshop. Contribution to DR8.2.

4.3 JRA2a: Distributed Scheduling in Interference-Limited Wireless Networks

Participants: CNIT-BO (P1), CNRS-EURECOM (P2), LNT-TUM (P3)

Leader: CNIT-BO

Responsible: Virginia Corvino

4.3.1 JRA Objectives

The objective of this JRA is the study of scheduling algorithms with a distributed approach in wireless networks. The emphasis will not be put on the design of specific scheduling algorithms directly, but rather on design methods for scheduling techniques with specific objectives to be defined (*e.g.*, throughput maximization, delay guarantee, etc.), since this will affect the method to be used. The study will be carried out through a mathematical approach to be then validated via simulation. Moreover, it is expected to apply the investigation to both a multi-cellular environment and other network types like those based on mesh topologies.

4.3.2 Background of Institutions / Researchers Involved

4.3.2.1 CNIT-BO

CNIT at University of Bologna gained expertise on scheduling with cross-layer approach over cellular systems in the presence of mixed realistic traffic over the last ten years. Their first study on scheduling was published in 2000 [39] and was related to scheduling over a single cell Time Division Duplex/Time-Code Division Multiple Access (TDD/T-CDMA) UMTS system in presence of mixed traffic according to the 3GPP classification [134]. Afterwards, due to the increasing interest in multi-carrier air interfaces, identified as candidate for future wireless systems such as UMTS LTE and WiMAX, the investigation was pushed toward this kind of air interfaces. In particular, scheduling over multi-cell Multi Carrier-Code Division Multiple Access (MC-CDMA) systems in presence of H.264 streaming video (and possibly FTP cross-traffic) with a cross-layer approach was studied [13]. Moreover, scheduling was performed in conjunction with application-suited buffer management techniques. In that work a formal separation of the scheduling and resource allocation functions was introduced and a cross-layer channel- and application-aware scheduler was designed. Nevertheless, all these studies were conducted on cellular systems according to a centralized approach. A preliminary work on scheduling in ad hoc networks was published [135], whose authors are also the researchers involved in this JRA, namely R. Verdone and V. Corvino.

4.3.2.2 CNRS-EURECOM

Over the last years, CNRS-EURECOM, and especially the researcher involved in this JRA, namely D. Gesbert, investigated the problem of resource allocation mainly from two different perspectives. In the first one, the problem of multi-cell optimization thanks to joint multi-cell power control and scheduling was considered [61], [68], [82], [83]. Mainly distributed schemes which approximate capacity maximizing solutions while requiring only a limited amount of data exchange between the cells or base stations have been considered. In the second perspective, RA schemes in conjunction with MIMO techniques were considered. This has be done first in the single cell context, and then generalized to a multi-cell context. Multi User MIMO (MU-MIMO) schemes and precoder design to separate users in the spatial domain were also investigated. The importance of scheduling is critical in order to guarantee the selection of users with high enough levels of orthogonality. In this problem the focus was mainly on the case of limited feedback, where scheduling and precoding must cope with partial description of the user's channels.

4.3.3 Description of Activities to be Performed

Scheduling over wireless shared channels is one of the most attractive issues nowadays, as in modern systems different traffic types, with different application requirements, need to co-exist over more and more complex air interfaces and over different kinds of networks. In fact, future wireless systems are designed to be adaptive (*i.e.*, implementing power control and link adaptation) and multi-carrier based. In such a scenario, a sensible management of so many degrees of freedom (*i.e.*, which subcarrier or group of subcarriers should be allocated to user *i*? Which modulation and coding format? Etc.) in the presence of differentiated, possibly time-variant, application requirements is crucial for system efficiency. In multi-cell scenarios, whilst in the past the “divide and conquer” approach was widely used, implying a static or semi-dynamic pattern of resource reutilization, more recent systems show a more aggressive reuse of spectrum throughout the network, as in UMTS. So, the problem of managing the resulting co-channel interference is raising. It is clear that scheduling plays a key role in order to maximize system performance whilst keeping under control interference rise. Moreover, besides cellular systems, wireless ad hoc and mesh networks attract raising interest in research due to their flexibility of application and deployment. Optimized scheduling in multi-cellular or multi-node scenario should be performed by a centralized unit able to collect all the information needed in order to take the best possible decision. However, such kind of implementation requires an amount of signalling (and a consequent delay in decision and actuation) which increases with the network size, until becoming unsustainable for the system. Due to these issues, scheduling in distributed networks without centralized control is more and more interesting.

The main topic to be investigated in this JRA is distributed scheduling in wireless networks with particular emphasis on design methods more than specific algorithm design. The approach applied to such study will be firstly mathematical, to be then validated via simulation. The target scenario of this JRA is a network composed of several devices (from now on denoted as *nodes*) deployed over a certain area and organized in hierarchical levels, as depicted in Figure 7. Nodes can be possibly of different nature. Then, we assume that the hierarchy could be defined according to two principles: functional or geographic. With the following meaning:

– *functional hierarchy:* a first analysis could be applied by considering that nodes at level 1 (the green circles in Figure 7) are provided with more advanced computational capabilities with respect to nodes at level 2 (the blue circles in Figure 7). An example of this scenario could be composed of the following sets of devices:
  - level 2 nodes are mobile terminals,
  - level 1 nodes are base stations (BSs),
  - level 0 nodes are controller units;

  links between level 2 and level 1 nodes are intrinsically unreliable due to the wireless medium, whereas it could be imagined that level 1 nodes are linked to the level 0 one via reliable links, such as optical fibres or fixed point-to-point wireless links. So, it is clear that such hierarchy is defined according to the different functional capabilities of the nodes deployed. The main topic to be investigated could be defined as "joint scheduling", which means scheduling of traffic coming from more than one level 1 node (even of different systems, *e.g.*, GSM, UMTS, WiMax, etc.) by a centralized controller (node of level 0 in Figure 7). Apart from studying the centralized approach, according to which the controller is some kind of "god" aware of all within the network and taking decisions for all nodes under its control, it can be even more interesting to study what happens in case the controller is only partially aware of the network characteristics or completely blind, leading respectively to the following behaviours:
  - *semi-distributed approach*: the level 0 node is not able to collect all the information needed to perform scheduling for the level 1 nodes under its control. So, the main issue is to identify a set of synthetic variables to be sent by the level 1 nodes to the level 0 node, in order to allow it to take scheduling decisions (*e.g.*, which metric for channel state evaluation, or for traffic load, for QoS requirement satisfaction, etc.). This is especially critical in case the level 1 nodes are heterogeneous *(i.e.*, they implement different technologies) and common metrics should be abstracted;
  - *fully distributed approach*: the level 0 node is completely blind with respect to level 1 nodes, so it remains excluded from the allocation process and scheduling decision is taken by each level 1 node independently, realizing an actually distributed approach;

– *geographical hierarchy:* still taking into account Figure 7, it can be imagined that the network is composed of only two kinds of device and hierarchically organized according to the geographic position of the nodes. In this case, nodes at level 0 are responsible for collection of data from other nodes deployed over a certain area (*e.g.*, this could be of interest for monitoring networks). If the area is large enough and/or nodes are tightly limited in transmit power (and, consequently, in transmission range, as for example in WSNs), some devices are not able to directly connect to the collector. So, the network can organize as follows:
  - level 1 nodes are devices able to directly connect to the level 0 node;
  - level 2 nodes are not directly connected to the level 0 node and, thus, connect to a level 1 node, realising multi-hop.

  As a comparison with the functional hierarchy, in such kind of hierarchy also the links between level 1 nodes and the level 0 node are wireless and, therefore, unreliable. Moreover, each level 1 node is also responsible for transmissions of the relevant level 2 nodes.

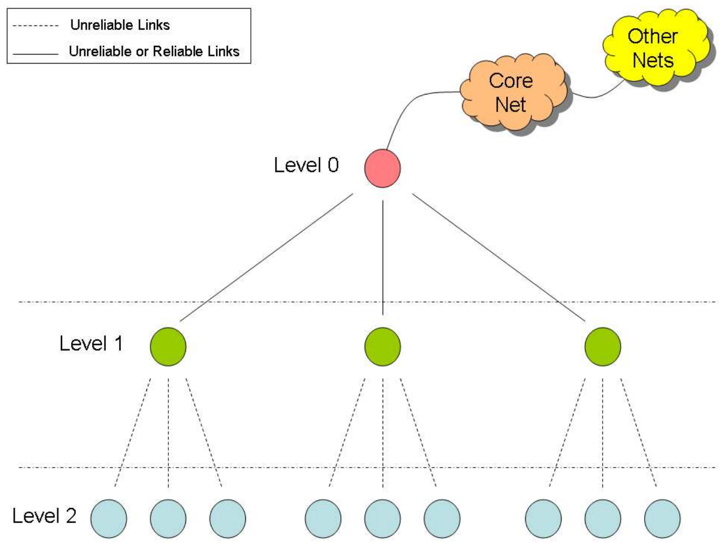

Figure 7: Target Scenario

An interesting case could be to consider a hybrid functional/geographical hierarchy, where level 1 and 2 nodes are devices with different functional capabilities but hierarchy is built according to a geographic criterion. A possible scenario could be the case of level 2 nodes which are sensors, level 1 nodes are mobile terminals with gateway capabilities and level 0 node is a base station collecting also control data to be sent to the opportune network.

The problems stated above will be studied using a mathematical approach, to be then validated via simulation, taking into account realistic deployments and channel characteristics.

4.3.4 Tools Used to Achieve the JRA Objectives

Since the JRA objective requires both analytical studies and simulation campaigns, a strong interaction between partners is required. At this aim, a six month researcher exchange has been planned. During this period it is expected to completely define the scenarios to be investigated and to start the JRA.

In order to meet the goal of the JRA, it is also expected that an exchange of models in scenario set up, mathematical analysis, simulation implementation, will be applied and fostered.

It is also expected that software exchange will be performed: in fact, both the institutions involved in the JRA have already expertise on scheduling and some software tools were already developed separately. Exchange of pieces of these tools is strongly recommended in order to speed up the integration process.

Finally, the inclusion of data measured by the single institutions within the common software tool is also encouraged.

4.3.5 Links to Other NEWCOM++ WPRs

Not foreseen by now.

4.3.6 Expected Outcomes

The following list includes a number of possible expected JRA outcomes. A more precise list will be decided after the preparatory phase (T0+8):

- common software modules,
- joint papers,
- short and medium term missions,
- organization of special issues,
- joint contributions to spreading of excellence and integration WPs.

4.3.7 Schedule of Activities

T0+4: Official start of the JRA. Start of the researcher exchange.

T0+10: End of the researcher exchange. It is expected that during these six months a definition of the specific scenarios to be investigated will be provided. The more tight exchange of ideas, models and pieces of software should be also performed, in order to fully exploit the potentiality of a researcher exchange. Then, the mathematical description of the system under investigation, the model to solve the problems defined, should be completed, and, possibly, the simulation framework defined.

T0+16: Expected publication of preliminary results.

T0+20: Possible outcomes: joint journal paper(s). Plan of contributions to DR8.2.

T0+22: Official end of the JRA. For this time, it is expected to have fulfilled the objective of the JRA and at least one journal paper is expected to be submitted. Contribution to DR8.2.

4.4 JRA2b: Scheduling in Cognitive Radio Networks

Participants: CTTC (P1), UPC (P2), CNIT-BO (P3)

Leader: CTTC

Responsible: Lorenza Giupponi

4.4.1 JRA Objectives

In cognitive radio scenarios, a more efficient utilization of the radio spectrum can be achieved. A hierarchical model is defined where primary (licensed) users are entities characterized by higher priority in a given frequency band (*e.g.*, cell phones, TV stations, emergency service, etc.) than secondary (unlicensed) users. The objective of the JRA is to study the scheduling of SUs in different available frequency channels, based on the availability of radio resources and on the activity of primary (licensed) users. A SU has to continually monitor the radio spectrum to identify available channels and their characteristics, and to reliably detect the presence of PUs, since, even if a SU is using a certain channel, a PU may start transmission in that channel at any time. This operation is referred to as spectrum sensing. Based on the results collected during the spectrum sensing operation, the SU can be properly scheduled on different frequency channels. Every time that it is estimated that a SU is causing harmful interference to a PU in a frequency channel, this channel has to be quickly vacated and the SU has to be scheduled on a different channel, initiating the process of the so called spectrum handoff.

4.4.2 Background of Institutions / Researchers Involved

4.4.2.1 CTTC

CTTC has background in cognitive radio and spectrum management research issues, especially gained during the realization of the IP IST FP6 projects WINNER and WINNER2. Currently, besides the activities related to NEWCOM++, CTTC is also involved in other projects related to cognitive radio issues. At European level, the most remarkable are the IST FP6 STREP project WIP, ICT FP7 STREP project PHYDIAS, and LOOP project, which is partially funded by Industry Spanish Ministry.

The researcher responsible for this JRA, namely L. Giupponi, has strong background in RRM and scheduling problems. She has been working in the IP IST FP6 projects E2R and E2R2, as well as in industrial projects funded by Telefónica Móviles, in Spain. Her PhD thesis dealt with Joint Radio Resource Management and scheduling in heterogeneous multi-cell, multi-RAT (Radio Access Technology), multi-service and multi-operator networks, based on fuzzy methodology improved with the learning capabilities of neural networks. Additionally, she has strong background in the study of cognitive networks.

4.4.2.2 UPC

The array and multi-channel processing group at UPC, and specifically the researcher involved in this JRA, namely A. Pérez-Neira, carries out fundamental research on physical layer technologies dealing with multiple diversity schemes, to face from single user to multiuser communications. The group activities on signal and fuzzy processing encompass also the data link and network layer aspects that relate with the physical techniques (*e.g.*, PHY-MAC cross-layer design). Special attention is paid to MIMO, Ultra Wide Band (UWB) and multi-carrier transports applied to 4th Generation (4G) wireless systems, either terrestrial or satellite.

4.4.2.3 CNIT-BO

CNIT-BO has a strong background on scheduling over multi-carrier based air interfaces and already has some preliminary works on scheduling over distributed systems, as extensively described in Section 4.3. Moreover, some studies related to the coexistence of different communication systems have been carried on, though not directly by the researchers involved in this WP, namely, R. Verdone and V. Corvino. The analysis performed so far mainly focused on the impact of mutual interference between narrowband and UWB communication systems [136] – [139]. Moreover, as far as sensing is concerned, an energy detector for wideband signals affected by Gaussian noise has been analyzed. Finally, a comparison between performance in terms of capacity region and cognitive users' data rate of the main hierarchical access model typologies (interwave, underlay and overlay techniques) is under investigation.

4.4.3 Description of Activities to be Performed

Cognitive radio is a new paradigm in wireless communications to enhance utilization of the limited spectrum resource. It is defined as a radio able to utilize available side information and to change its transmitter parameters based on the interactions with the surrounding environment where it operates, in order to efficiently use the radio spectrum. The basic idea is that a cognitive radio is able to properly sense the spectrum conditions and, to increase efficiency in spectrum utilization, it seeks to underlay, overlay or interweave its signals with those of the licensed users, without impacting their transmission.

The underlay paradigm encompasses techniques that allow communication by secondary users assuming they have knowledge of the interference caused by its transmitter to the receivers of the primary users. Specifically, the underlay paradigm mandates that concurrent primary and secondary transmissions may occur, as long as the interference generated by the secondary users is below some acceptable threshold.

The overlay paradigm allows the coexistence of SUs and PUs in the same frequency channel, as long as the secondary transmission can overlay the primary ones for example by means of codification techniques. The enabling premise is that the SU transmitter has knowledge of PUs' codebooks, and possibly of its message as well, when the PU begins its transmission. While this is impractical for an initial transmission, this assumption may hold for a message retransmission, for example in a cooperative scenario where SUs exploit the knowledge of the PUs' message in order to mitigate the interference at the PU receivers. More in particular, the SUs can utilize this knowledge by assigning part of their power to their own secondary communications, and the remaining power to relay the PUs' transmission. By a careful choice of this power split, the increased interference at the PU receiver, due to the effect of the SU communications, can be compensated by the SU relay.

The interweave paradigm is based on the idea of opportunistic communications, and was the original motivation for cognitive radios. The idea came about after observing the existence of temporary space-time frequency voids, referred to as spectrum holes, which are not in constant use in both licensed and unlicensed bands. These gaps change with time, and can be exploited by SUs for their communications.

In this JRA the objective is to study scheduling techniques for at least two of the paradigms of cognitive radio: interweave and underlay.

As for the interweave paradigm, we will focus on scheduling techniques among different available frequency channels, to efficiently utilize the bandwidth left unused in a cellular TDMA/FDMA (Frequency Division Multiple Access) system (*e.g.*, a GSM/EDGE Radio Access Network - GERAN), where a decentralized secondary system, represented by an overlay ad-hoc network, opportunistically operates. The general system architecture is shown in Figure 8. The fundamental constraints for this secondary system are: 1) it uses the time slots/frequency channels (*i.e.*, data channels) unused by the primary GERAN system, 2) its operation does not degrade the performances of the primary system, 3) there is no exchange of signalling information between the primary and the secondary system, to facilitate the secondary usage of spectrum, that is, the PUs are not cognitive aware. We will consider a scenario where SUs can opportunistically access the radio resources of a GERAN base station selecting the unused time slots in the most appropriate available frequency channel (see Figure 8), depending on sensed parameters such as the cell load or the perceived interference patterns. We will compare performance results obtained considering different decision making inputs (*e.g.*, number of users operating in a certain frequency channel, measured interference temperature, etc.) to the scheduling problem.

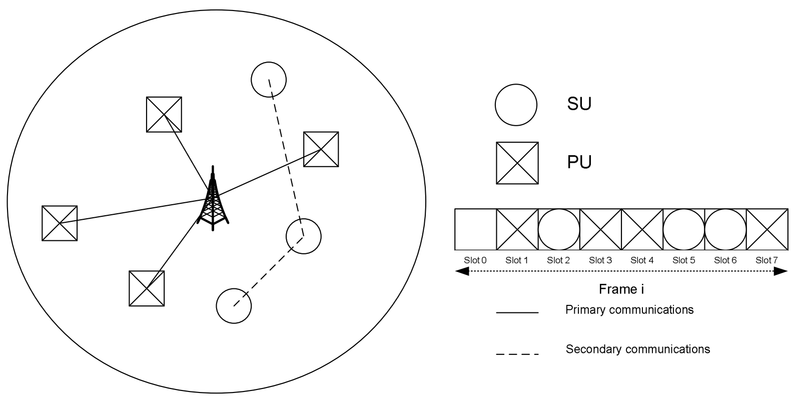

Figure 8: Opportunistic Use of Available Time Slots in Frame *i*

As for the underlay paradigm, we will make use of the concept of interference temperature, in order to evaluate the interference that SUs are causing to PUs receivers. We will focus on a decentralized architecture where SUs autonomously and automatically make decisions about how to schedule among the different frequency channels, and when it is the most appropriate instant to realize the scheduling operation. The way how SUs make the decision of switching to a different frequency channel, due to the fact that they are causing harmful interference to a PU, is a challenging problem. In fact, a scenario in which PUs and SUs coexist is characterized by high uncertainty deriving from different components: the decentralization of the operation, the hostile nature of the wireless channel, the interference caused by other SUs which is a major component of disturb, the multiple decision making inputs which have to be considered, etc.. Spatial considerations in terms of frequency reuse should be made in this kind of scenarios. Examples of these spatial considerations may include the following, as also shown in Figure 9: 1) when the distance between the SU transmitter and the PU receiver is less the r_n, where r_n is defined as a “no talk” radius, the SU is not allowed to talk; 2) the further the SU from the PU receiver, the higher its transmission power can be, etc..

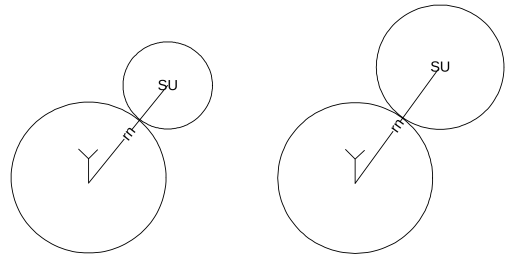

Figure 9: Example of Spatial Considerations for Frequency Reuse in Cognitive Radio Networks

For all this reasons, it is our opinion that the challenges rising in a cognitive radio scenario can be properly met by using techniques based on incomplete knowledge representation and qualitative reasoning. In particular, in this JRA we propose to use fuzzy logic to deal with the incompleteness, uncertainty and heterogeneity of a cognitive radio scenario, and fuzzy control to implement the decision making process in it.

4.4.4 Tools Used to Achieve the JRA Objectives

The activity proposed will be realized at CTTC in the framework of the Access Technology Area. UPC will cooperate with CTTC through discussions. Additionally, CNIT-BO will supervise the work realized at CTTC and will provide inputs in terms of statistical study of PUs behaviour and exchange of this statistical information among PUs.

4.4.5 Links to Other NEWCOM++ WPRs

This JRA has a natural contact point with the activities realized in the framework of WPR.9, which deal with spectrum management research issues. In fact, some of the activities proposed in the context of WPR.9 could be interesting inputs for this JRA. For example, in the context of WPR.9 some activities have been proposed with the objective of realizing spectrum measurements. Additionally, another WPR.9 proposed activity focuses on the study of cooperative techniques among SUs in a cognitive radio environment, in order to exchange sensing information which would lead to a better secondary usage of spectrum. The output of this second activity proposed in WPR.9 in terms of sensed spectrum conditions, could be an interesting input to the scheduling schemes that will be studied in this JRA.

4.4.6 Expected Outcomes

The expected outcomes by this JRA are the publication of joint papers with the different institutions involved. It is more difficult to evaluate at this stage the possibility of realization of other kind of joint activities in the context of this JRA, considering the reduced workload of the responsible institution (CTTC) in WPR.8. The realization of other joint activities will probably significantly depend on the interest that will be shown in this JRA by the two other partners involved (UPC and CNIT-BO).

4.4.7 Schedule of Activities

T0+4: Official start of the JRA.

T0+9: The first activities that will be studied are those related to the interweave paradigm, since this paradigm is the initial motivation for cognitive radio. Considering that the most important challenge in the interweave context is the detection of PUs, it will be shown that some level of interference will have to be admitted at the PUs receiver.

T0+15: The assumption of a certain level of interference in the PUs will naturally lead us to the study of the underlay paradigm, which will be based on the introduction of fuzzy logic methodology in a scheduling decision framework. Plan of contribution to DR8.2.

T0+22: Particular attention will be paid to the problem of maintaining the aggregated interference temperature value at the PU receiver below a certain value, which is an open issue in the literature. Contribution to DR8.2.

4.5 Subsection 4.5 – JRA3a: Scheduling Techniques for Heterogeneous Networks

Participants: NKUA/IASA (P1), CNIT-BO (P2)

Leader: NKUA/IASA

Responsible: Nikos Dimitriou

4.5.1 JRA Objectives

As a result of the massive deployment of coexisting wireless networks, mobile users often have several choices of collocated WLANs to connect to. This situation is exacerbated by the deployment of large scale mobile third-generation systems operated by major network operators, as well as other, smaller unregulated networks. In fact, mobile user chips already exist which support multiple standards and, additionally, there has been a significant amount of work in creating flexible radio devices capable of connecting to *any* existing standard. It is therefore reasonable to expect that in the near future users will have the option to connect to different networks and to switch dynamically between them on a real-time basis, based on the offered throughput and/or price.

The objective of this JRA will be to analyze the dynamics of the vertical handover between standards. We assume that users can switch air interfaces in the time-scale of seconds, as opposed to the case where users are not capable to handover. We will assume that parallel connections to both air interfaces are available, allowing each user to switch between air interfaces at rates faster than the typical session duration. In addition, we employ a game-theoretic perspective in order to calculate the socially optimal states (Nash equilibria) of the system.

4.5.2 Background of Institutions / Researchers Involved

4.5.2.1 NKUA/IASA

NKUA/IASA group members that will be involved in this activity, have a solid background in the area of vertical handover and heterogeneous RRM through participation to the EU-project URANUS. In this project the focus of a specific sub-activity is on proposing algorithms for dynamically scheduling users among different air interfaces with the problem of vertical handover between wireless service providers. The dynamics of handover between two coexisting wireless standards and the consequent exploitation of the offered diversity by the use of multi-standard terminals is being investigated using elements of Game Theory. This work has been published so far in [140] and [141].

4.5.2.2 CNIT-BO

CNIT-BO has a strong background on scheduling over multi-carrier based air interfaces. Moreover, this institution cooperated in NEWCOM Department 7, where many issues related to RRM, also for heterogeneous networks, were investigated. Particularly, their researchers contributed actively through writing deliverables but, mainly, through a very successful JRA with LNT-TUM, with whom a C++ simulation framework where realistic multi-cell scenario can be considered, was set up. This software was designed in order to be also extended to the heterogeneous network scenario.

4.5.3 Description of Activities to be Performed

The dynamics of handover between two coexisting wireless standards and the consequent exploitation of the offered diversity by the use of multi-standard terminals is proposed to be investigated. The potential capacity benefits of mobile-initiated vertical handovers are substantial. However, it is important to choose the correct VHO criteria in order to achieve optimum load balancing and (global and social) equilibrium states.

The dynamics of this process have several interesting aspects. Firstly, due to the lack of a central controlling authority, mobile users become selfish and, even though users now have more choices to connect to, they still need to compete for the finite resources of nearby access points. Moreover, the repeated structure of the process makes users rely on past information available to them, in order to learn to adapt to the environment. To make things worse, since only local information about the past states of the system may be available (*e.g.* the average service throughput per user), it is not clear how users may use this information in an effective manner. It is clear from above, that this process can be modelled in terms of a non-cooperative game.

4.5.4 Schedule of Activities

This activity will build on the work that will have been done by the other aforementioned activities. Its scope and objectives will be re-visited in a subsequent phase of NEWCOM++, with the possible inclusion/participation of some other WPR8 partners.

5 ACTION PLAN

The Action Plan for WPR8 was discussed and approved by participating institutions during a joint WPR8-10-11 meeting held in Catania, Italy, on March 13-14, 2008. According to the outcome of that meeting, the objectives of WPR.8 and the list of JRAs presented in Section 2 of this Deliverable, have been defined. The scientific activities are then specified and scheduled as follows.

The period of time ending at T0+6, when this Deliverable is released, was devoted to:
- description of state of the art on scheduling and radio resource assignment, as reported in Section 2;
- definition of the JRAs as reported in Section 4;
- harmonization of the activities planned within the JRAs, obtained through a thorough discussion and agreement about objectives of the WP, common basic definitions, and an analysis of the most promising tools and methods to design scheduling and radio resource assignment techniques (see Sections 1 and 3).

Starting at T0+6, with end planned at T0+22, the four JRAs related to Tasks 1 and 2 (JRA1a, 1b, 2a, 2b) will run in parallel. A meeting is scheduled at T0+11 to monitor the state of JRAs, and check whether a deeper exchange of information among JRAs is needed to harmonize the activities. Also, the detailed scenarios defined within the four JRAs will be discussed, to find points of contact for possible harmonization. DR8.2, due at T0+22, will report on the final scientific achievements of those four JRAs.

At T0+18, JRA3a will start, with an end planned at T0+34, when DR8.3 will be released, based on the results achieved. Possibly, other JRAs might be defined, as an evolution of JRA1a, 1b, 2a or 2b towards heterogeneous networks, after T0+22.

Each JRA is expected to act through integration of the skills of the participating partners, providing some among the following list of outcomes:
- exchange of knowledge / software modules / data;
- publication of joint papers;
- exchange of researchers for short or long term visits;
- joint supervision of PhD candidates;
- offers of joint tutorials;
- offers to edit journal special issues;
- offers to organize special sessions at conferences.

Besides the activities performed within the JRAs, WPR.8 participants agreed on plans for providing non-JRA related inputs to other NEWCOM++ WPs. More specifically:

- WPR.9, 10 and 11 are the most closely related to WPR.8; therefore, strong interaction is expected. In particular WPR.8, 10 and 11 will continue having joint meetings. DR11.1 includes a section on scheduling and radio resourse assignment for opportunistic networks which is synchronized to this Deliverable in terms of definitions, and concepts described. The three WPs will be in close contact, through the action of the WP leaders. Network scenarios and performance metrics are expected to be shared. Also, similar assumptions concerning link level should be set;
- inputs will be provided to Integration and Spreading of Excellence WPs, according to the requests of the respective plans, on a JRA basis.

Finally, it was decided that in 2009 a public workshop will be organized jointly with other EC projects; the detailed topic will be defined based on the initial outcomes achieved by the four active JRAs, at T0+11. In 2010, a joint WPR.8, 10 and 11 workshop will be organized, focussing on a topic of common interest to the three WPs.

CONCLUSIONS

In this first Deliverable of WPR.8, the State of the Art of the literature on scheduling and radio resource assignment has been reported. In particular, firstly a survey on basic scheduling notions and techniques has been presented. Starting from this investigation and having noticed that a common language on this topic is still missing in the literature, an effort has been put in the formalization of the "scheduling" and "adaptive radio resource assignment" concepts, and some commonly agreed definitions have been introduced. Furthermore, a detailed description of the main scheduling strategies related to the three Tasks in which the WP is organized, respectively devoted to multi-carrier and space-division based systems, distributed wireless systems and heterogeneous networks, has been provided.

Then, the identification of the most used scheduling concepts has been employed to perform a detailed analysis of them according to different points of view, such as their main characteristics, the tools and methods used for their design, their major advantages and drawbacks. This analysis has been performed in order to open a discussion aiming at identifying what should be the criteria and methods to be considered when designing new scheduling and adaptive radio resource assignment algorithms, which are the most suitable and powerful tools to be used, which characteristics are mandatory and which approaches are recommendable.

Having set the requirements for the design of future scheduling and adaptive radio resource assignment techniques, JRAs have been set up for each Task, according to the background and the declarations of interest that Partner involved in the WP presented. In particular, for each JRA the objectives, the background of the Institutions involved and their role within the JRA, a detailed description of the activities to be performed, the tools to be used in order to achieve the JRA objectives, possible interaction with other NEWCOM++ WPs, the expected outcomes and the schedule of the activities, have been provided. A graphical synthesis of the JRAs to be performed within WPR.8, with the relevant partners involved and the interactions with other NEWCOM++ WPs, is reported in Figure 10.

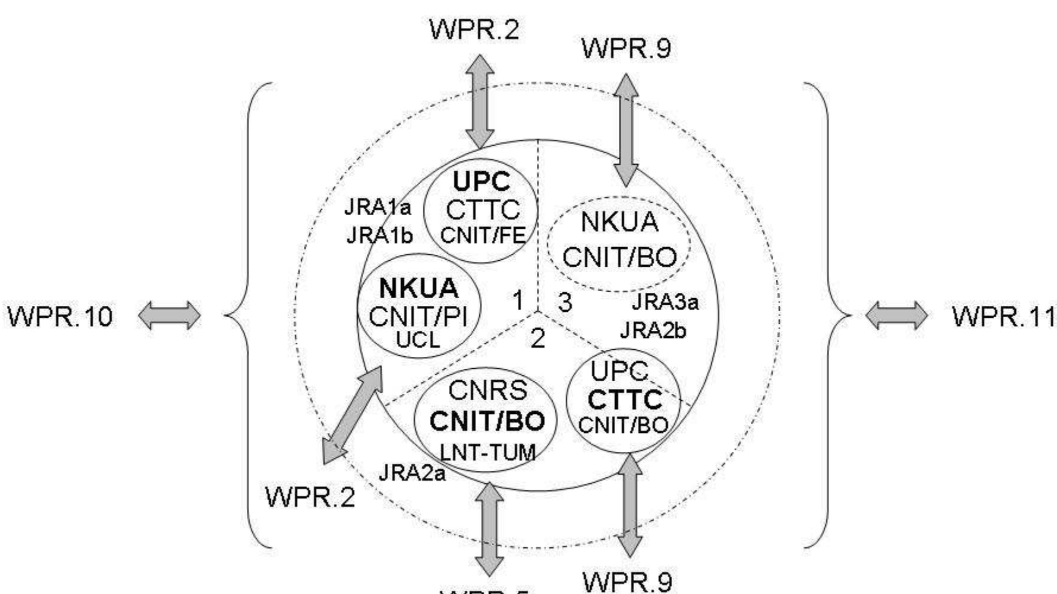

Figure 10: WPR.8 JRAs Organization

As a final remark, it is expected that, besides the achievement of the main objectives of this WP, namely the design of fast radio resource assignment and scheduling techniques according to new design paradigms, using a cross-layer implementation and considering both centralized and distributed approaches, another important objective of this WP is the interaction with other research groups involved in these topics. First of all, natural exchange of ideas and tools with the other NEWCOM++ WPs belonging to the Network Cluster, namely WPR.9, WPR.10 and WPR.11, is foreseen. Moreover, interaction with other NEWCOM++ WPs is recommendable, since they can provide useful inputs, like WPR.2, and introduce innovative approaches, like WPR.5, which can be really valuable for this WP. Nevertheless, interaction with other European Projects devoted to the study of wireless systems is also expected, like with COST Action 2100 on "Pervasive Mobile & Ambient Wireless Communications", where topics ranging from physical to network layer are investigated.

LIST OF ACRONYMS

2G	2nd Generation
3G	3rd Generation
3GPP	3G Partnership Project
4G	4th Generation
AAA	Authentication Authorization and Accounting
AC	Admission Control
AMC	Adaptive Modulation and Coding
AP	Access Point
BER	Bit Error Rate
BS	Base Station
BSC	Base Station Controller
BW	Bandwidth
CDMA	Code Division Multiple Access
C/I	Carrier-to-Interference
CIF – Q	Channel condition Independent Fair Queueing
CPU	Central Processing Unit
CQI	Channel Quality Indicator
CRRM	Common Radio Resource Management
CSI	Channel State Information
CSMA	Carrier Sensing Multiple Access
CTS	Clear to Send
EDF	Earliest Deadline First
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
GERAN	GSM/GPRS/EDGE Radio Access Network
GSM	Global System Mobile
HLR	Home Location Register
HO	Handover
HSPA	High Speed Packet Access
IP	Internet Protocol
IWFQ	Idealized Wireless Fair Queuing
JRA	Joint Research Activity
LA	Link Adaptation
LCD	Low Constraint Data
LDD	Long Delay Data

LP	Linear Programming
LTE	Long Term Evolution
MAC	Medium Access Control
MC	Multi Carrier
MC CDMA	Multi-Carrier Code Division Multiple Access
MIMO	Multiple Input Multiple Output
MSR	Maximum Sum Rate
NAV	Network Allocation Vector
NoE	Network of Excellence
NP-complete	Non-deterministic Polynomial-time complete
NRT	Non Real Time
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMB	Opportunistic Multi-Beamforming
OSA	Opportunistic Spectrum Access
PC	Power Control
PF	Proportional Fair
PRC	Proportional Rate Constraints
PS	Packet Scheduling
PU	Primary User
QoS	Quality of Service
RA	Resource Allocation
RAN	Radio Access Network
RAT	Radio Access Technology
RNC	Radio Network Controller
ROC	Region Of Convergence
RR	Radio Resource
RRM	Radio Resource Management
RSS	Received Signal Strenght
RT	Real Time
RTS	Request to Send
RU	Resource Unit
SBFA	Server Based Fairness Approach
SDMA	Space Division Multiple Access
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SoA	State of the Art

SU	Secondary User
T-CDMA	Time-Code Division Multiple Access
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UDD	Unconstrained Delay Data
UMTS	Universal Mobile Telecommunication System
UTRAN	UMTS Terrestrial Radio Access Network
UWB	Ultra Wide Band
VHO	Vertical Handover
WAF	Wireless Adapted Fair
WFS	Wireless Fair Service
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
WP	Work Package
WSN	Wireless Sensor Network

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