Cross-Layer Radio Resource Allocation: the Journey so Far and the Road Ahead

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***Abstract*—The cross-layer concept originated almost ten years ago with the aim of taking the most advantage from the difficult wireless media to break the barriers imposed by the layered transmission. One of the domains where cross-layer design has been more investigated is Radio Resource Allocation, since current and future networks need to provide wireless connectivity to heterogeneous users, offering many different data traffic types. Nonetheless, new paradigms are emerging in the field of wireless communications, like cognitive radios, wireless systems with relays and Multiple Input Multiple Output (MIMO) systems, where the potential advantages of cross-layer scheduling are still largely unknown. Moreover, in spite of a large literature on cross-layer, in the most cases different focuses and perspectives, biased by the application(s), are addressed, thus, there is lack of a general framework. The main goal of this paper is not to provide a state of the art on cross-layer scheduling and resource allocation, since this would result maybe in a heterogeneous list of scientific contributions. Rather, we are interested in performing a cataloguing of the work so far, trying to identify common tools and general frameworks used for cross-layer resource allocation, justify them by means of specific network examples and highlight open issues and challenges to be faced. Nevertheless, a preliminary objective of this work is to introduce a set of definitions which can be hopefully agreed by the scientific community.**

I. Introduction

The cross-layer concept originated almost ten years ago with the aim of taking the most advantage from the difficult wireless media. Ad hoc networks and data packet transmission opened a myriad of transmission possibilities, and motivated to break the barriers imposed by the layered transmission. In [1], cross-layer design has been defined as a "protocol design done by actively exploiting the dependence between protocol layers to obtain performance gains. This is unlike layering, where the protocols at the different layers are designed independently". In the same work an interesting and exhaustive overview of the cross-layer design paradigms present in the literature, with the discussion of the main relevant characteristics and issues, is provided. Since then, despite the short time, the relevant literature has exploded, focusing on functionalities ranging from the physical (PHY) [2] to the application layer [3], from network [4] to transport layer [5]. This happened thanks also to the multiplication of the number of possible communication scenarios: cognitive radios, (Multiple Input Multiple Output) MIMO systems, wireless systems with relays are some examples to mention but a few.

One of the domains where cross-layer design has been more investigated is for sure Radio Resource Allocation (RRA). In fact, multi-user packet scheduling over shared channels is one of the most attractive issues for researchers, as in modern wireless systems different traffic types, with different application requirements, need to co-exist over the air interface. After the exploitation of application-aware scheduling concepts borrowed from computer science, like Earliest Deadline First (EDF) [6] and Generalized Processor Sharing (GPS) [7], [8], it became soon clear that the possibility of exploiting channel fluctuations realizing channel-aware techniques was really beneficial in systems where the spectrum is scarce and expensive and, thus, to be used at its best. The most important classes of strategy with this aim are based on the concept of Opportunistic Scheduling [9], which however may rise some fairness problems for users perceiving bad channel quality for long time; Proportional Fair and Wireless Adaptive Fair [10] algorithms introduce fairness guarantee while exploiting channel variability. However, current and future networks need to provide wireless connectivity to heterogeneous users, offering many different data traffic types: File Transfer Protocol (FTP), audio, video, web browsing, et cetera. For this reason, cross-layer design in RRA is considered as one of the main instruments for network optimization [11], [12].

System capacity performance improves dramatically if the number of simultaneously served users can be increased. Hence, additional amount of signal processing and diversity is required at both the transmitter and the receiver. Diversity is further justified if not only the PHY layer but also higher layers take advantage of it. Therefore, cross-layer design is the second identified aspect that makes more viable advanced processing techniques and spatial diversity techniques. In any case, layered implementations have to be considered when a modular implementation of the system is highly desired.

With no exception, all future (and present) wireless systems will experience a remarkable bandwidth shortage. Clearly, intelligent and innovative PHY-layer technologies and management schemes for the available radio resources constitute the only way to harmonize two contradictory concepts such as scarce bandwidth and stringent QoS requirements. Additionally, when targeting fully reconfigurable systems, it is mandatory to consider cross-layer design, providing an opportunity to create synergies between two groups of researchers: i) from

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PHY and ii) MAC/RRM/routing fields, which have ignored each other to a large extent. It is assumed that during almost two decades the research community in Europe has achieved excellence in PHY technologies involving joint design and use of linear pre-processing, pre-coding, spectrum shaping, modulation format, array processing at the transmitter and receiver sites, terminal processing, sequence detectors and decoding. However, additional effort with a different perspective is required in order to do not further delay the implementation and the best use and adoption of physical layer innovations. In the following paragraph these innovations are introduced in order to justify its relevance.

As already mentioned, new paradigms are emerging in the field of wireless communications, like cognitive radios, wireless systems with relays and MIMO systems. In these cases, the potential advantages of using cross-layer techniques in scheduling over shared channels are still largely unknown. Moreover, in spite of so much work on cross-layer, in the majority of the cases this has been done under different focuses and perspectives, biased by the application(s) they address. There is lack of a general framework. However, trying to identify the most commonly used methods to deal with cross-layer implementations, tools such as optimization, game theory or fuzzy logic have been consolidated as important to formulate and solve most of the cross-layer problems.

Since, as already discussed, cross-layer design is basically applicable to any functionality performed in a wireless system, in this work we focus on radio resource allocation. However, the main goal of this paper is not to provide a state of the art of the literature on cross-layer scheduling and resource allocation. In fact, due to the dependence on the specific application(s) and scenario under consideration, it is high the risk that this would result just in a heterogeneous list of scientific contributions. Rather, we are interested in performing a cataloguing of the work so far, trying to identify common tools and "general frameworks" used when it comes to cross-layer resource allocation, justify them by means of specific examples and highlight open issues and challenges to be faced. Before proceeding, it is worth putting some order in the nomenclature related to wireless scheduling. So, a preliminary objective of this work is to introduce a set of definitions which can be hopefully agreed by the scientific community.

The remainder of this paper is organized as follows: in Section II some definitions related to the issue of resource allocation are provided. In Section III, some of the most currently investigated wireless scenarios which could take advantage of cross-layer resource allocation are presented, with the relevant challenges to be faced and goals to be pursued. In Section IV, the way to design cross-layer scheduling strategies is discussed presenting characteristics to be considered, possible tools to be used, and relevant drawbacks. Finally the Conclusions.

II. Some Preliminary Definitions

In the literature, the terms *scheduling* and *resource allocation* (RA) are sometimes used as synonyms [13], [14], sometimes not [15], [16]. So, it is worth introducing a clarification by distinguishing these two concepts.

Many definitions for scheduling in wireless systems have been provided over the last fifteen years. 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" [17], 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 (*note*: Quality of Service) in terms of throughput and delay" [11], are provided. Trying to abstract a unique definition, scheduling is a *Radio Resource Management (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 data streams supported by a certain user.

Since above the definition of "resource" is introduced, it would be worth trying to specify what it is in the peculiar contest of wireless systems, which is quite hard, since it depends on the type of system under consideration. In order to generalize this concept, 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*. Thus, 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, it is composed of the time slot over which transmission is allowed, the carrier frequency and the relevant bandwidth, the modulation and coding format, the power level and, possibly, the transmitting spatial dimension.

According to the definition of RR, a Resource Unit (RU) can be consequently defined as the smallest RR assignable or, alternatively, the RR allowing the minimum amount of data to be transmitted. However, since an RR (and consequently an RU) is composed of both discrete (*e.g.*, time slot) and continuous dimensions (*e.g.*, power level), it is actually impossible to define a numerable set of resources offered by a certain system. Nevertheless, it could be useful introducing a "reduced" definition of resource intended as the set of only discrete dimensions, 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 Spatial Division Multiple Access (SDMA). In such situation, it is indeed possible to compute the maximum number of resources offered by the system. Thus, the problem of scheduling is about the *distribution of orthogonal resources among competing users*, where 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.

It is now possible introducing the differentiation between scheduling and radio resource allocation (or assignment). In multi-user environments, scheduling operations become more and more complex as the number of users competing for the wireless shared channel increase. In this case, since fully optimized scheduling could require an infeasible complexity, it may be useful to split it in some steps. In fact, the scheduling functionality provides an answer to these two main questions: who will be the next user to be allocated? Which resources will the user be assigned with? The answer to the first question could be provided working on an abstract concept of radio resource, without knowledge of the specific air interface. On the opposite, for the second answer the knowledge of the particular air interface is compulsory. Although this approach has been already presented in few recent works [15], [18], [19], none of them explicitly defines it as a general framework. The concept of Adaptive Radio Resource Assignment could be defined as *the allocation of a specific set of RRs to a certain flow according to the contingent state of the system*. This definition has two main implications: firstly, when performing RRA the air interface structure of the system under investigation is known and considered in the process; secondly, the adaptiveness of the process can be related to one or several time-varying characteristics of the system, such as the wireless channel, the state of queues, the number of users, QoS requirements, the state of some layers in the protocol stack, et cetera. 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 multi-user 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 [15], [16], [20], whose potential is high for future wireless systems, as discussed below, thanks also to the complexity reduction introduced.

III. Goals and Challenges in Wireless Applications

According to the specific network scenario under consideration, the objectives to be pursued and the challenges to be faced can change, especially for cross-layer design. In the following, some examples of wireless networks considered as a hot topic are described, emphasizing the aim they are deployed for, and the related issues to be dealt with.

A. MIMO systems

When reviewing the mechanisms used in communication systems to enable the coexistence of users, *i.e.*, the so called multiple access techniques, we classify them into PHY-layer driven and MAC-layer driven multiple access schemes. In PHY-layer driven techniques, the concern is about how to coordinate multiple user transmissions without taking into account the nature of the transported traffic and the services within. This is a paradigm that is changing in order to combat the detrimental effects of the wireless channel and increase spectral efficiency. Among the PHY-layer driven techniques, we distinguish: Frequency Division Multiple Access (FDMA), TDMA, CDMA and SDMA. The development of multiple antenna techniques introduced an extra dimension in the multiple access problems since the mobile users in a wireless network can be separated depending on their spatial positions [12], [21]. Among the PHY-layer technologies, antenna arrays can provide tremendous capacity advantages without requiring extra bandwidth and power. However, most of the determination to use antenna arrays in communication systems decays when either complexity or cost issues come into play. A true view, but not adequate, is that wireless radio is, at system level, much more complicated and subject to market competitiveness. More precise would be to say that there are no layers on the mentioned applications. However, without cross-layer activities the excellence, if any, of the PHY-layer innovations will be no longer recognized neither used. Whenever upper layers do not contribute to a best use of the PHY layer, coordination will be an unaffordable objective. It is also true that antenna arrays should be employed in a constrained way, by resorting to scalability and differential redundancy.

B. Wireless Networks with Relays

In the last years a new communication paradigm has arisen in the world of wireless networks starting from new applications, such as ad hoc networks based on decentralized architectures, where nodes help each other to ensure information transfer from source nodes to destination nodes. This paradigm is named cooperative communication and is enabled by the broadcast nature of the wireless medium: wireless network nodes have not only the role of sources or sinks, but can be viewed as a resource usable to help or improve one or more ongoing communications [22]. This concept is now considered for many different wireless applications, including cellular systems where some nodes acting as relays are introduced to extend coverage or increase capacity. One or more nodes act as relays cooperating with a source node to realize a spatially distributed system for the transmission of information. This technology introduces new degrees of freedom in the communication process and extends the set of wireless resources to be managed. Also in these applications cross-layer design is an important tool, whereas new issues are open for the design of scheduling and RRA techniques handling relays as a RR. In cooperative communication, a relay can be used according to a specified protocol defining the way of sharing the wireless channels among source and relays [23]. There are fixed relaying schemes where the RRs are divided deterministically between source and relays, as in amplify-and-forward relaying and decode-and-forward relaying. There are also adaptive relaying schemes, such as selective relaying and incremental relaying, where the channel is adaptively assigned to relays according to the channel state between source and relays, between relays and destination, and between source and destination [24]. In other words, in adaptive schemes relays are resources that can be activated and assigned to active sources. Moreover, the relays themselves require RRs, such as power, slots, carriers, making the RRA problem more challenging and open to investigation.

C. Cognitive Networks

Cross-layer design can play a very important role in communication protocols for cognitive radio networks [25], [26]. The design of the main cognitive radio functionalities, *i.e.*, spectrum sensing, spectrum management, spectrum handoff and spectrum sharing, requires the cooperation among different communication layers. The spectrum sensing functionality is in charge of getting information about spectrum utilization. The performance of cognitive radio networks at all layers strongly depends on this functionality, laying at PHY layer. The spectrum management functionality aims at efficiently using the radio spectrum left unused by primary users, by selecting the most appropriate frequency channel to use anytime and anywhere. This function has to be cross-layer defined, since it depends on functionalities defined at different layers of the communication stack: the frequency channel decision making procedure should be carried out by considering multiple criteria such as interference at the primary user receivers, pathloss in the available frequency channels, wireless link errors, primary user activity, spectrum availability, routing and transport requirements, application requirements, etc. [27]. The spectrum handoff functionality is in charge of vacating a primary channel due to, *e.g.*, the sudden activation of a primary user in that channel, or degradation of secondary user QoS. This is closely related to operations carried out at different communication layers cooperating with spectrum sensing, to gain information about other frequency channels, spectrum management, to select the most appropriate frequency channel where to move the communication, and spectrum sharing, to realize a coordinated access with other secondary users active in the frequency channel selected to realize the spectrum handoff. In addition, the most important challenge related to this functionality is the resulting latency from the handoff procedure, which highly depends on the latency of the spectrum sensing operation, so that a cross-layer design in this sense is recommended. Finally, it is worth mentioning that spectrum sensing is characterized by numerous challenges, and some of them can be addressed by considering cooperative approaches, such as cooperative detection, mitigation of aggregated interference generated by multiple cognitive radios at the primary receivers, or the capability of sensing the whole spectrum. However, the implementation of cooperative approaches requires a strict collaboration with the spectrum sharing functionality. As a result, a cross-layer design between spectrum sharing and spectrum sensing is required.

IV. Cross-Layer Scheduling and Radio Resource Assignment Design

The aim of this Section is to identify proper tools to design cross-layer scheduling and RRA algorithms. The main advantages and drawbacks related to each approach presented will be emphasized. Before providing their descriptions, a discussion on the main characteristics a cross-layer scheduler should have, is performed.

A. Characteristics

From the nature of the wireless medium, a mandatory characteristic of a scheduling algorithm should be adaptiveness to channel variations to use spectrum at its best. However, one of the issues still to be addressed is which kind of metric should be used to estimate channel quality: while Signal-to-Interference-plus-Noise Ratio (SINR) can be used when channel has no selective effects, viceversa a vector of channel parameters could be preferable if the channel is frequency-selective, or multi-antenna systems are considered. Nevertheless, the relevant frequency of updating should be related to channel variation speed and to the algorithm requirements, considering that future systems promise to provide high bit rates also at high user speed. Faster channel prediction/estimation/tracking schemes could be investigated to ensure the best possible match between the Channel Quality Indicator (CQI) level and the actual channel conditions the node experiences when assigned with the respective Adaptive Modulation and Coding (AMC) combination.

QoS management is still far away from being sufficiently addressed, both in the case of multi-service networks and of ad hoc applications. A preliminary work should be performed towards the identification of synthetic parameters to tackle the (possibly) different requirements set by each application, both in form of input data and as parameters to be adjusted in the algorithm, such as message structure, upper layer protocol behavior, source coding/encoding behavior.

Due to the high spectrum reuse, wireless systems are interference-limited. Most of the works on scheduling still handle the problem of channel awareness only as fading awareness. Traditionally interference is managed through power control. However, this "last minute" solution prevents any exploitation of interference prediction. Moreover, the always increasing reduction of scheduling time (*e.g.*, 2 ms in HSDPA) has a highly dangerous potential: in a very few ms the number of users allocated (and their parameters) can change many times. A possible solution could be "planning" interference in a network through the use of careful RRA policies.

As a final remark, an important issue is fairness. However, it should be discussed if its conventional definition still holds in modern wireless networks. In fact, in the presence of many different applications characterized by different requirements, the traditional concept of fairness is actually outdated: each user is not interested in how much he is served with respect to other users, but rather with respect to his own specific requirements. This introduces a new concept of fairness, definable 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.

B. Tools

1) Game Theory: 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 RRA 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 RRA strategies, and 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 [28]. As an alternative to the traditional approach, it was recently proposed to exploit the so-called cooperative games, where players essentially build trust into one another, aiming at improving their own rate, via some form of bargaining. In the recent literature, its application was limited to spectrum sharing in cognitive radio, and in the case of cooperative beamforming [29]. However, it was also used earlier in the context of cooperative OFDMA resource allocation [30]. This approach can be suited to any kind of air interface as long as network architecture is distributed, as in peer-to-peer and ad hoc networks, and is commonly implemented in a channel-adaptive way. However, game theory approaches do not guarantee neither throughput maximization nor optimal resource distribution, since each user tries to get as many resources as possible selfishly, which is not a good policy from a network viewpoint, whose objective is trying to serve as many users as possible according to at least their minimum performance requirement. Moreover, this mathematical tool is quite complex, so, it could be mainly used as a good benchmark of how a set of nodes behaves in a network without centralized control.

2) Fuzzy Logic: Fuzzy logic is a mathematical framework, aiming at realizing sophisticated control systems considering that many times real problems cannot be efficiently expressed by means of mathematical models. So, fuzzy set theory models the vagueness existing in real world problems. According to it, when A is a fuzzy set and x a relevant object, the proposition "x is a member of A" is not necessarily true or false, but it may be true or false only to some degree, which ais commonly expressed by a number on the closed interval $[0, 1]$, where 0 and 1 represent, respectively, the total denial or affirmation of the membership. Fuzzy logic provides an inference morphology enabling approximate reasoning capabilities applicable to knowledge based systems. To implement decision making processes, it makes use of the so called Fuzzy Logic Controllers (FLCs), whose essential part is a set of linguistic control rules based on expert knowledge in the form: IF (a set of conditions are satisfied) THEN (a set of consequences can be inferred). In essence, the FLC provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy: this appears very useful when processes are too complex for analysis through conventional quantitative techniques or when the available sources of information are interpreted qualitatively, inexactly or uncertainly. The main weakness of FLCs is the dependability of their decisions on the way how membership functions and fuzzy inference rules are set. To encompass this limit, fuzzy logic is often combined with learning algorithms based on neural networks or genetic algorithms.

3) Optimization Formulation: Wireless network design is usually conducted in one out of two different styles: for PHY-layer researchers, the bandwidth is the main concern and its optimization is pursued often in terms of Shannon capacity; for higher-layer researchers, since it is mostly impossible to have analytical solutions, the design criteria is often heuristic. Trade-offs between these approaches aim at identifying better practical implementations. Many wireless RRA problems can be formulated as constrained optimization problems from network or individual viewpoint. If the optimization goal, the inequality constraints, and the equality constraints are all linear in the parameter function, the problem is called a *linear program*. If either the optimization goal or the constraint functions are nonlinear, the problem is called *nonlinear program*. One special kind of nonlinear program is the *convex optimization* problem, where the feasible set is convex, the optimization goal and the constraints are convex/concave/linear functions. In this case, any locally optimal point is also globally optimal. If the feasible set contains some integer sets, the problem is called *integer program*. About drawbacks, the challenges of convex optimization are to recognize and model the problems as convex optimization, for which there are many tricks. To find closed-form solutions, one of the most important methods for constrained optimization is the Lagrangian method. However, in case of nonlinear and nonconvex constraints and optimization goal, the Lagrangian multiplier function is hard to differentiate and the optimal points are hard to obtain. Some approximations can be obtained under specific conditions: i) approximate the nonlinear or nonconvex function by a parameterized function; ii) omit unimportant parts within a certain working range (*e.g.*, capacity in terms of Signal-to-Noise Ratio for high SNR is convex). About integer/combinatorial optimization, most of these programs are Nondeterministic-Polynomial-hard (NP-hard) problems unsolvable in polynomial time. These are related to meet desired objectives when the values of some or all of the variables are restricted to be integer. In practice, many parameters can have only integer or combinatorial value, like modulation level, coding rate, route selection. Moreover, even for some continuous parameters such as transmission power, the real implementation has finite granularity, leading to limited integer values as choices. To solve integer/combinatorial problems we can resort to relaxation and decomposition, brand-and-bound, and cutting plane. Beyond these methods, there are other methods such as dynamic programming, matroids, and greedy algorithms. In most practical scenarios, integer programming and other types of continuous programming are usually combined together realizing mixed programming. Clearly, solutions are problem-oriented.

C. Final Remarks

In wireless communication systems, two important detrimental effects decreasing network performance are channel's time-varying nature and channel state information. A general strategy to combat these effects is dynamic RRA and scheduling based on channel conditions. Methods such as optimization, game theory or genetic formulation, 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 behavior 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 high complexity and 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 allowing 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 the number of parameters needed to describe the system increases, the mathematical complexity of the scheduling and RRA optimization problem increases as well. 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 processes, thus, it should be considered also as a tool to incorporate heuristics.

V. Conclusion

One of the domains where cross-layer design is of capital interest is radio resource allocation. In spite of a large literature, there is lack of a general framework. In this paper, after introducing a set of definitions to be hopefully agreed by the scientific community, a cataloguing of the work so far has been provided, identifying common tools, also by means of specific network examples, and highlighting the main open issues.

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