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Spectrum and Radio Resource Management

Oriol Sallent, Lorenza Giupponi, Jad Nasreddine, Ramon Agustí, and Jordi Pérez-Romero

Optimized Usage in Cognitive Wireless Networks

Wireless technologies are rapidly evolving to allow operators to deliver more advanced multimedia services. High-speed packet access (HSPA) for uplink and downlink is seen as an intermediate evolutionary step since the first wave of wideband code division multiple access (WCDMA)-based networks rollout, while evolved universal mobile telecommunications system (UMTS) terrestrial radio access networks (E-UTRAN) are the long term perspective for the Third Generation Partnership Project (3GPP) technology family. Similar paths are drawn from the 3GPP2 around the evolution of code division multiple access 2000 (CDMA2000). Moreover, the IEEE 802 working groups are producing an evolving family of standards, such as 802.11 local, 802.15 personal, 802.16 and 802.20 metropolitan and 802.22 regional area networks.

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Furthermore, the regulatory perspective on how the spectrum should be allocated and utilized in a complex and composite technology scenario is evolving. The evolution is toward a cautious introduction of more flexibility in spectrum management together with economic considerations on spectrum trading. This new spectrum management paradigm is driven by the growing competition for spectrum and the requirement that the spectrum is used more efficiently [1]. Instead of the classical fixed spectrum allocation to licensed systems and services, which may become too rigid and inefficient, the possibility of using flexible spectrum management (FSM) strategies that dynamically assign spectrum bands in accordance with the specific traffic needs in each area [2] recently have been considered. There are different FSM scenarios presenting different characteristics in terms of technical, regulatory, and business feasibility. While a fully enabled FSM scenario can be envisaged in a rather long-term perspective, there are already some basic FSM scenarios that are becoming a reality [3]. An example is spectrum refarming, providing the possibility to set up communication on a specific radio access technology (RAT) in different frequency bands (e.g., refarming of global system for mobile communications (GSM) spectrum for UMTS or HSPA communications). Another case for FSM arises from the so-called digital dividend, which corresponds to the frequencies in the UHF band that will be cleared by the transition of analog to digital television. The cleared spectrum can be utilized by mobile TV or cellular technologies like UMTS, LTE, WiMAX, etc., and also for sharing flexibly spectrum between smart radio technologies. The exploitation of the so-called TV white space, which refers to portions of spectrum that are unused either because there is currently no license holder for them or because they are deliberately left unused as guard bands between the different TV channels, is another opportunity for FSM mechanisms.

The multiplicity of RATs and network operators, their different characteristics, and the flexibility in spectrum management point out a challenging scenario that introduces relevant opportunities to increase efficiency. Certainly, the heterogeneous wireless network vision may be realized in a number of techno, regulatory, and business scenarios, which will require diverse solutions and technologies for a proper exploitation of such opportunities. In any case, the framework envisaged above can only be fully accomplished by further enhancing the radio access networks (RANs) toward cognitive network (CN) technologies. A CN has a cognitive process that can perceive current network conditions and then plan, decide, and act on those conditions. The network can learn from these mechanisms and use them to make future decisions [4]. Thus, CNs have the potential to utilize the large amount of unused spectrum in an intelligent way.

Introduction

This article presents a framework to achieve an optimized dynamic spectrum and radio resource usage in heterogeneous wireless network and multioperator scenarios. The envisaged technical solution follows a layered approach, where joint radio resource management (JRRM) and advanced spectrum management (ASM) mechanisms are identified at both intra- and interoperator levels. The interaction between layers, together with reference operative time scales, is described and accompanied by an illustrative case study. Moreover, the importance of CN functionalities is highlighted as a key enabler. Finally, the different steps of the cognition cycle are further developed, with particular emphasis on guiding principles to be applied to the different stages.

The ultimate objective of this article is to present and develop a framework for technical solutions leading to an optimized utilization of the spectrum and radio resources. Clearly, the solution framework requires several strategies to be developed synergistically and, for this to succeed, the support of CN features is a must.

The rest of the article is organized as follows. First, the technical challenges raising in future wireless scenarios are presented together with the envisaged technical solution, which is based on a four-layer architecture involving radio and spectrum management strategies at both intra- and interoperator levels. A case study is presented, illustrating the interlayer operation. Second, the envisaged layered strategy is integrated into the cognitive cycle and some hints into the applicable mechanisms and solutions for the different steps are provided. Particular emphasis is placed on the decision-making processes, which are further developed for the different layers. Finally, the article concludes with a summary of the main concepts discussed.

Envisaged Technical Solution

Scenario Considerations

Mobile cellular services in a given geographical area are usually provided by several competing operators. Operators usually deploy more than one RAT in the same coverage and try to differentiate themselves not only by the technology itself, but also by using different business models.

For a given operator, the network deployment is usually designed to support the expected traffic level at the busy hour. Certainly, the inherent dynamic nature of the mobile cellular scenario makes it impossible to predict accurately the offered traffic profiles along time and space. Current offered traffic may differ from the planned level because of, e.g., 1) fluctuations due to statistical call/session generation processes in the short term (i.e., below a few minutes time scale) and/or 2) variations in the long term (e.g., within the whole busy hour period) of the current average offered load value with respect to the planned one for a variety of reasons, e.g., faster service penetration than predicted, actual spatial traffic distribution different from the one considered in the planning exercise, etc. In either case, the operator faces mismatches between the required capacity and the available capacity. Spare available capacity could lead to unnecessary waste of scarce radio resources, which could perhaps be used by other operators or RATs. On the contrary, in case of lack of available capacity, nondesirable Quality of Service (QoS) level is provided to customers. In this case, RAN extension can be a good solution for long-term deviations, although it may require weeks or months until new infrastructure is added. Consequently, new potential solutions providing adaptability in diverse time scales can be considered in order to face the above traffic variations.

In that respect, a number of base-line techniques have been identified, proposed, and analyzed in recent years to cope with heterogeneous wireless networks with FSM capabilities [5].

- JRRM: Process that enables the management (assignment, deassignment) of users to different radio access systems for a fixed spectrum band allocated to each of these systems. Vertical handover (i.e., handover between different systems) constitutes the key procedure in support of JRRM.
- ASM: Process that enables the dynamic management (assignment, deassignment, sharing) of spectrum blocks within a single or between different radio access systems.

These base-line strategies target to facilitate the most efficient radio resource utilization possible while providing a seamless experience to mobile users. The different resource optimization techniques have to be integrated into a coherent framework, given that each use case poses special problems of resource utilization and requires a different approach to achieve the optimal resource allocation. In this respect, [6] discusses the fundamental aspects and proposes a corresponding architecture explaining the basic functional modules through a set of use cases.

Proposed Solution: A Layered Approach

The proposed solution illustrated in Figure 1 intends to cope with actual traffic conditions through the most suitable mechanism from a multilayer structure. The ultimate objective of the layered approach would be to achieve an automatic, self-adaptive operation, where suitable mechanisms are activated at a suitable time. To this end, four different layers are identified.

1) Intraoperator JRRM: At this layer, current traffic demand is managed by means of algorithms applied over the pool of resources belonging to a given operator. These algorithms flexibly assign users to different RATs of the same operator. In that respect, this layer operates over a fixed spectrum band assigned to each of these RATs.
2) Interoperator JRRM: At this layer, current traffic demand is managed through an alternative operator providing access to the required services in the scenario at a certain time by assigning users flexibly to different RATs of a different operator. A trading agent implemented as a meta-operator may be the actor that provides the bridge among different operators.
3) Intraoperator ASM: At this layer, current traffic demand is managed by means of dynamic spectrum management algorithms, which come up with suitable spectrum reassignment to cells and RATs within a given operator. Intraoperator ASM rearranges the spectrum bands allocated to that particular operator, enabling the dynamic management of spectrum blocks within a single or between different RATs. Consequently, it determines the capacity for each different RAT of the operator.
4) Interoperator ASM: At this layer, current traffic demand is managed with the help of additional resources that the operator rents to or buys from other operators. Interoperator ASM considers the granularity of the associated spectrum to each RAT and thus it is generally applied to substantial pieces of radio spectrum (e.g., renting 5 MHz band to deploy an additional UMTS carrier).

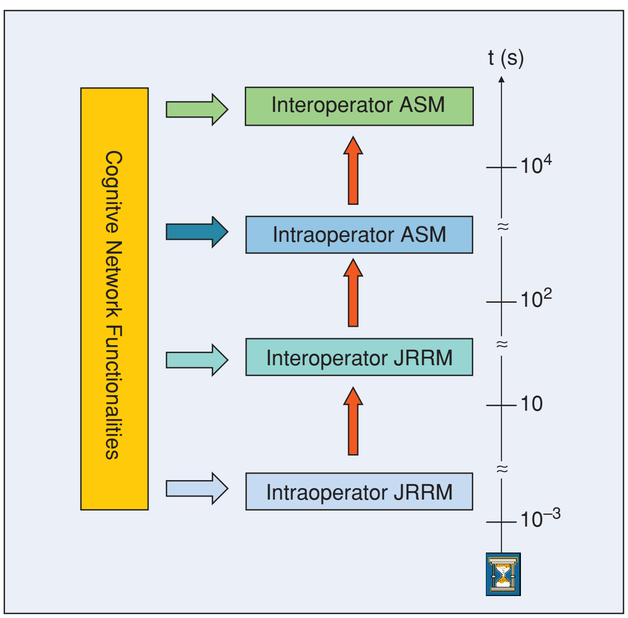

FIGURE 1 Layered intra-/interoperator and JRRM/ASM approach.

Interlayer Operation

The four strategies identified above are also distinguished by the time scales at which they are applied as illustrated with some reference values in Figure 1. In particular, JRRM strategies operate at the shortest time scale (in the order of minutes and below) whereas ASM strategies operate at a longer time scale (at least in the order of minutes).

The main objective of the integrated layered approach is to achieve a synergistic operation of the different mechanisms, leading to an overall optimized exploitation of the available resources. To this end, triggering events activating the suitable layer at the suitable time are needed to adapt to the time and space-variant traffic demand.

The envisaged normal flow from the perspective of a reference operator with a certain deployment of heterogeneous RANs in a given scenario is described in the following:

1) By default, the reference operator will attempt to provide the service to its customers through its own deployed infrastructure, thus intraoperator JRRM is applied upon every service set-up request. Intraoperator JRRM mechanisms should provide seamless service across the different RANs and cell sites. For a reference operator OP#1, intraoperator JRRM solutions are applied for a given spectrum $B_{OP\#1}$ allocated to OP#1 and a given spectrum split between the different RATs deployed by OP#1 (i.e., $B_{RAN\#1}$ and $B_{RAN\#2}$), as illustrated in Figure 2.
2) In case of short-term difficulties in providing accessibility to OP#1's network (i.e., a service request should be blocked or provided with insufficient QoS), interoperator JRRM mechanisms may be activated to maintain high QoS perception for the user. In this case, the service can be set-up with satisfactory QoS through another operator with whom agreements have been established. Taking into account that interoperator JRRM mechanisms imply some kind of revenue sharing model between the involved operators, the reference operator may establish triggering actions tending to skip interoperator JRRM and move to intraoperator ASM at an early stage.
3) Assuming that good JRRM algorithms are implemented, if key performance indicators (KPIs) at a medium to long-time scale point out degradation in QoS levels, this may indicate that JRRM mechanisms have reached their limits with the current assignment of spectrum in the scenario and the current traffic conditions. In such case, the operator may question whether the spectrum mapping to cells or RATs is suitable in the actual radio network state. This will be targeted by intraoperator ASM mechanisms, which will look for a suitable spectrum or RAT assignment fitting the current conditions, eventually implemented by dynamic network planning. The outcome of the intraoperator ASM algorithm is a more suitable system operation point. That is, intraoperator ASM solutions are applied for a given spectrum $B_{OP\#1}$ allocated to OP#1 as illustrated in Figure 2. It is worth noting that, in case that for instance RAN#2 supports all services provided by RAN#1 with higher spectral efficiency, then the ideal outcome of intraoperator ASM would be $B_{RAN\#2} = B_{OP\#1}$. However, if RAN#1 is a legacy technology, the operator may be interested in further exploiting its investment in RAN#1 and to continue providing service to legacy terminals, etc. and, therefore, not all the allocated spectrum to OP#1 could be assigned to a single RAN.
4) In case the synergized operation between JRRM and intraoperator ASM reaches its limits, which again could be observed by QoS degradation, it can be concluded that the amount of available resources for the operator is not enough to cope with the offered traffic. In such case, interoperator ASM mechanisms are envisaged as a source of getting additional spectrum.

Figure 3 illustrates how interoperator ASM mechanisms manage different amounts of spectrum to different operators; i.e., $B_{OP\#1}$ and $B_{OP\#2}$.

The above strategies need to be fed and supported by mechanisms that allow extracting the network status and operation point, prior to defining the best possible actuation on the network. This is facilitated by the CN element in Figure 1 that monitors and captures the network status at different levels, which are of interest for the different layers.

Case Study

Peter is a business customer with a high QoS profile. He owns a multi-RAT terminal. He is on the way to the train station and makes a call. Initially, intraoperator JRRM assigns the connection to the 3G-RAT in OP#1 and performs several horizontal handovers as Peter is moving across the area. Reaching an area where 3G coverage is

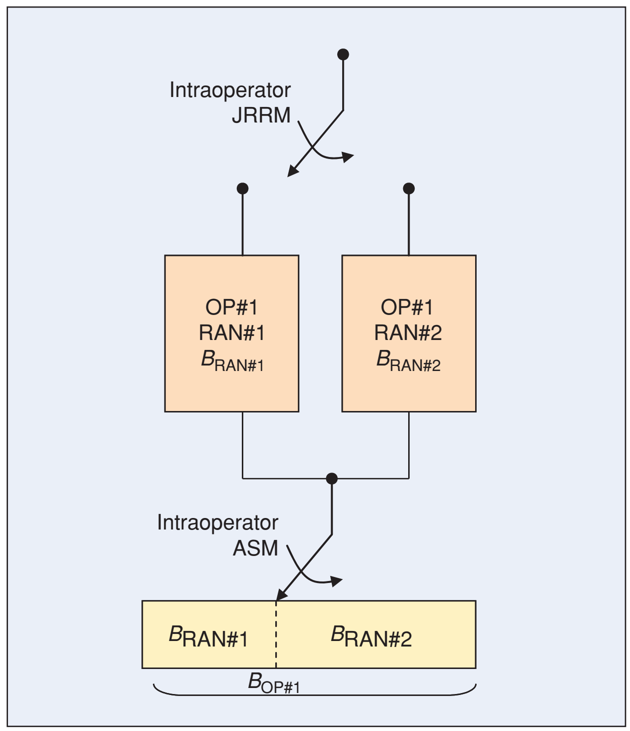

FIGURE 2 Illustration of intraoperator mechanisms: JRRM and ASM.

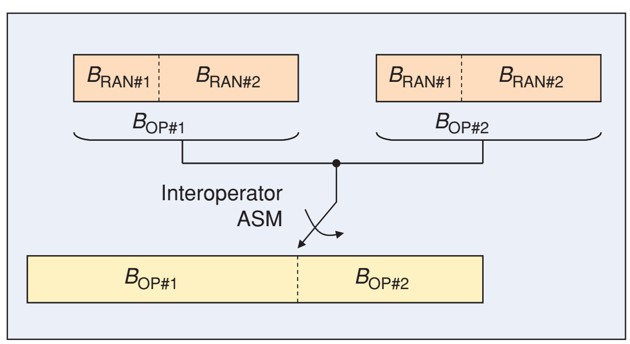

FIGURE 3 Illustration of interoperator ASM mechanism.

poor, intraoperator JRRM decides a vertical handover to the 2G-RAT in the same operator.

Once at the train station, serious delays in train schedules occur. Consequently, the station is more crowded than usual. Peter wishes to call home to say that he will be late. His own operator's network is seriously blocked, since difficulties in finding new cell sites in the area have prevented the operator to extent its network deployment in the last months and, therefore, the deployed capacity cannot cope with such a worst-case traffic demand. Nevertheless, Peter is able to make the call through another operator's network, thanks to interoperator JRRM agreements. Even though the revenue for the service goes to the serving operator, Peter's operator has been able to meet the agreed QoS in terms of accessibility. The overall interoperator process has been transparent to Peter.

Given that a high number of users are being redirected to other operators through interoperator JRRM, intraoperator ASM is activated to find a spectrum assignment that fits better with the actual space/time traffic distribution. Additional 2G-RAT carriers are assigned in the area, so that further Peter's calls are supported again through intraoperator JRRM mechanisms over the upgraded pool of radio resources assigned to 2G-RAT. The dynamic planning associated with intraoperator ASM has significantly reduced the number of interoperator exchanges in the train station area. However, the QoS provided in a nearby area with the new planning is not fully satisfactory. Even though the network performance from an overall perspective (i.e., averaged over the train station and nearby area) has improved and, therefore, intraoperator ASM has revealed to be effective in this case, the operator targets better overall performance. Consequently, interoperator ASM mechanism is triggered at a later stage to get additional spectrum from other operators. Assignment of additional spectrum to current cell sites would be a feasible solution meanwhile new cell sites can be deployed.

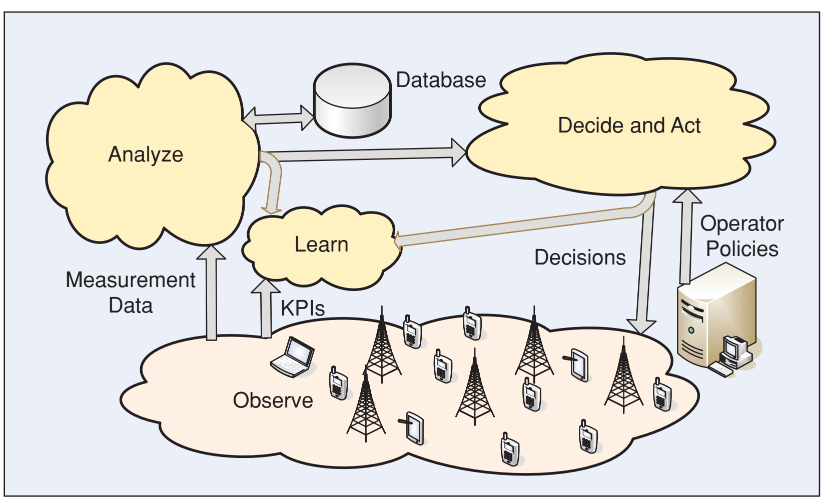

FIGURE 4 Integration of spectrum and radio resource management strategies in the cognitive cycle.

Exploiting CN Mechanisms

Mobile communication networks are dynamic in nature. Dynamism arises from multiple dimensions: propagation conditions, traffic generation processes, interference conditions, mobility of radio transceivers, etc. Thus, changing network and scenario conditions may degrade network performance and QoS. Consequently, modern networks must provide mechanisms to adapt to changes by introducing CN features. CN refers to a network being able to sense the radio environment (sensing the radio context, service context, location context and user context), automatic reasoning (interpreting the radio environment), self-actuating (reacting to the changes), self-tuning (tuning the radio and implementation parameters) and self-healing (fault management). A CN exploits the cognitive cycle [7], [8], as illustrated in Figure 4.

The proposed layered approach, considering JRRM or ASM mechanisms at both inter or intra operator level, should be integrated in the cognitive cycle to target the highest possible efficiency and advanced realization. To this end, the following subsections provide some hints into applicable mechanisms and solutions.

Observe

The observation of the network status involves a large number of measurements and metrics. Measurements and metrics can be obtained at different network elements (e.g., mobile terminals, base stations). Measurements relevant for a particular function of the cognitive cycle need to reach the network element(s) where the corresponding function is implemented. Typically, in 2G or 3G cellular networks, this is associated with a central node. Nevertheless, there is a clear trend in future wireless network toward decentralization of the intelligence and decision making processes, even residing some cognitive cycle functionalities at the mobile terminal (e.g., as envisaged in IEEE P1900.4 [9]). Measurements and metrics of interest may be at connection level (e.g., path loss from terminal to cell site, average bit rate achieved over a certain period of time, etc.) or at system level (e.g., cell load, average cell throughput achieved over a certain period of time, etc.).

Analyze

This stage considers relevant inputs obtained from the observation phase and its objective is the identification of relevant changes in the network status affecting the provisioned QoS levels. Furthermore, the analysis may consider the dynamics on intercell interactions (i.e., mutual interference from any pair of cells) as a key indicator reflecting the radio interface conditions and its evolution due to changes in requested services, spatial distribution of users, etc. For example, intercell interactions can be represented in smart forms, such as the so-called coupling matrix [10]. For the particular case of a WCDMA system, the coupling matrix is defined as the Jacobian matrix of the interference system of equations in uplink and, correspondingly, the Jacobian matrix of the total transmitted power system of equations in downlink. In order to illustrate that the coupling matrix has interesting mathematical properties that can be used as performance indicators, Figure 5 shows a high correlation between the spectral radius (i.e., the eigenvalue with the highest modulus) of the coupling matrix and the outage probability (i.e., the probability that a given user is not reaching the target QoS).

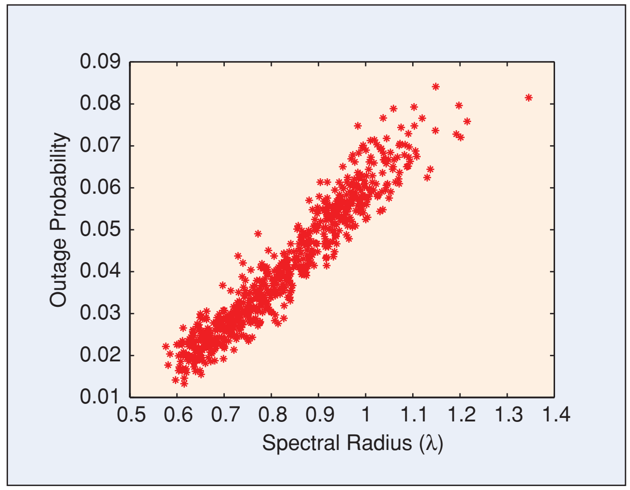

FIGURE 5 The outage probability as a function of the spectral radius for different mobile positions and cell loads.

Learn

Many strategies can be envisaged as learning procedures with the ultimate goal of acquiring knowledge. In the context of CNs, machine learning has been widely considered as a particularly suited framework, with multiple possible approaches [11]. Among them, reinforcement–based learning can fit into the specificities of many spectrum and radio resource management scenarios. Actually, reinforcement learning is the problem faced by an agent that has to learn a behavior through trial-and-error interactions with a dynamic environment. On each step of interaction, the agent receives as input some indications of the current state of the surrounding environment, and according to them it then chooses an action to generate as output. This action changes the state of the environment, and the value of this state transition is communicated to the agent through a scalar referred to as reinforcement signal. The main focus relies usually on algorithms that follow or estimate a relevant gradient. The gradient seems to provide a powerful and general heuristic basis for generating algorithms that are effective and often simple to implement.

In particular, reinforcement learning mechanisms have been introduced as part of intraoperator JRRM methodologies, with the objective of allowing and maintaining a guaranteed QoS under dynamic conditions in the heterogeneous wireless access network scenarios. More specifically, [12] defines the user dissatisfaction probability as an indicator of undesired QoS level accounting for the fraction of users not reaching the desired bit rate requirements. The reinforcement learning mechanism takes the current measured dissatisfaction probability as reinforcement signal. Deviations between the actual value of the reinforcement signal and the target dissatisfaction probability are used to tune the membership functions of a connectionist fuzzy-neural based network implementing the intraoperator JRRM solution [12]. In this respect, as an illustrative example, Figure 6 shows the percentage of non-satisfied users in a heterogeneous scenario where UMTS, GSM EDGE Radio Access Network (GERAN) and WLAN RANs coexist along time. It can be observed that, even though at a given time a sudden increase in the number of users in the scenario occurs (i.e., 100–150 users), the reinforcement learning mechanism allows attaining the target QoS (3% and 10% dissatisfaction probability—DP—in the examples shown in Figure 6).

Decide and Act

The proposed layered approach includes four different strategies, whose objective is synergistically achieving the highest possible efficiency in spectrum and radio resource usage. Different triggers will support the interlayer operation, then defining the most convenient strategy layer at a certain time and space. Each layer is

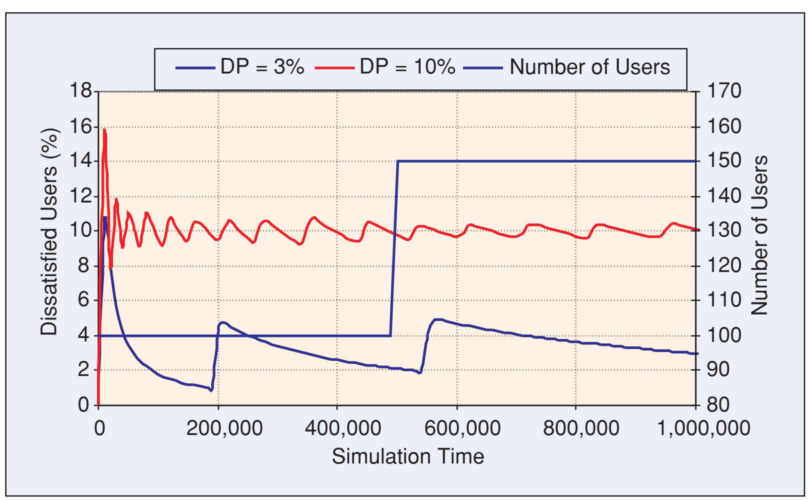

FIGURE 6 Illustration of the dynamic measurement of the percentage of non-satisfied users when reinforcement learning mechanisms are applied.

characterized by an algorithm that implements the "decide and act" stage of the cognitive cycle. The specific algorithm applied at each level accepts many possible forms and approaches. In this respect, the following subsections develop some considerations related to the corresponding possible solution frameworks.

Intraoperator JRRM

As discussed previously, the additional dimensions introduced by the multiplicity of available RATs provide further flexibility in radio resource management and, consequently, overall improvements may follow with the use of intraoperator JRRM strategies. In this context, a key JRRM functionality is the RAT selection, which is devoted to decide the RAT that a given service request should be assigned to. This applies at session initiation (i.e., the initial RAT selection procedure) as well as along an on-going session (in this case, the RAT selection procedure may lead to a vertical or intersystem handover, changing the access network the mobile is currently connected to).

Selecting the proper RAT is a complex problem due to the number of involved variables; including the network accessibility, radio resource availability, RAT suitability to support the QoS for the requested service, operator preferences, user preferences, etc. Some possible guiding principles for RAT selection are:

1) Service-based RAT selection. A service-based RAT selection policy is based on a direct mapping between services and a prioritized list of preferred RATs.
2) Load-balancing RAT selection. This policy will distribute the load among all resources as evenly as possible. That is, whenever a mobile station can attach to more than one base station and/or RAT, the new call can be directed to the base station and/or RAT with the greatest number of available channels, i.e., the least loaded base station. Service balancing considerations could also be included [13].
3) Interference-based RAT selection. The wide sense of this principle intends to anticipate the effects that the allocation of a certain connection request to a certain cell and RAT will cause in terms of interference. Then, different criteria could be used for the RAT selection so that the interference tends to be minimized.

Clearly, an advanced RAT selection algorithm may integrate several of the above principles. For illustrative algorithms and strategies, the interested reader is referred to [14]–[15].

Interoperator JRRM

Two different roles are identified in interoperator JRRM: the home operator (H-operator, i.e., the operator the user has a contract with) and the serving operator (S-operator, i.e., the operator who is actually providing the service to the user). The interoperator JRRM mechanism has to be transparent to the user and the price charged to the user should be the price p charged by the H-operator under normal operation. Then, the total revenue generated by the service is shared between the two involved operators, so that the H-operator will keep a fractional revenue $(1-\alpha)p$, while the S-operator will receive αp, where $0 \leq \alpha \leq 1$. Depending on the selected value for α, different business models can be envisaged (e.g., $\alpha = 1$ where the S-operator gets all revenue; $\alpha = \eta$ with $\eta \leq 1$ is the normalized S-operator load and thus revenue is shared depending on load conditions in the serving network, etc.).

It was shown in [16] that interoperator JRRM agreements allow improving the revenue for the involved operators compared to the case where no interoperator agreements are established.

Interoperator JRRM mechanisms can be implemented either through direct agreements between any pair of operators, which is very similar to international roaming, or through a third trusty party (i.e., meta-operator [5]), which allows the pooling of different networks.

Intraoperator ASM

The objective of the intraoperator ASM methodology is to find the appropriate spectrum assignment to cells and RATs that satisfies the maximum number of users at all periods of time for the current assignment of spectrum bands. Thus, intraoperator ASM is an inherently dynamic process that should react in front of substantial variations in the scenario, particularly to space or time traffic distribution. This process can lead 1) to rearrange the frequency assignment plan (i.e., dynamic network planning) while keeping the same total available amount of spectrum, 2) to release, globally or locally, some spectrum blocks, which can be used by other RATs or placed in market for interoperator ASM purposes, 3) to request additional spectrum to interoperator ASM mechanisms.

Intraoperator ASM copes with 1) cell load variations, which may be associated with an increase or decrease in the number of users or in the requested service characteristics (e.g., increase or decrease of the required bit rates) and/or 2) intercell interference conditions variations, which may be associated with changes in spatial user distribution. An illustrative intraoperator algorithm, applied to a single WCDMA network, is illustrated in Figure 7 in the form of a flow diagram. The algorithm is developed in order to come up with a suitable spectrum assignment in the scenario (i.e., mapping of carriers to cells) [10]. When relevant variations in the traffic distribution occur, this means that some of the cells that share the affected carriers are experiencing high interactions and should no longer use the same carrier. Thus, the detection of this event is a very important issue in the overall ASM methodology to guarantee the required QoS levels.

Significant capacity gains (in the order of 40%) have been reported in the literature when applying dynamic intraoperator ASM compared to reference frequency planning schemes [10].

Interoperator ASM

Following the initial assignment of spectrum rights and obligations to users, circumstances may change causing initial license holders to wish trading their rights and obligations to others. The possibility to trade radio spectrum is argued by many actors to be a critical factor in the promotion of more efficient radio spectrum use [17]. Spectrum trading is a powerful way of allowing market forces to manage the assignment of radio spectrum rights and associated obligations and it is a significant step toward a market-based spectrum management regime. Clearly, trading of spectrum is made much more powerful when it is combined with policies aimed at promoting liberalization in use (i.e., relaxation of the conditions attached to a spectrum license dealing principally with services and technologies). As liberalization provides greater flexibility, it means that spectrum trades are able to seize the opportunity for greater gains.

The key tools that a regulator needs to deploy in order to allow market forces to manage spectrum are auctions, trading and property rights (e.g., limits on emissions). In addition, some powers to address anticompetitive behavior may also be required. All these ingredients are the foundational aspects of interoperator ASM, which would implement the specific spectrum transactions between involved parties.

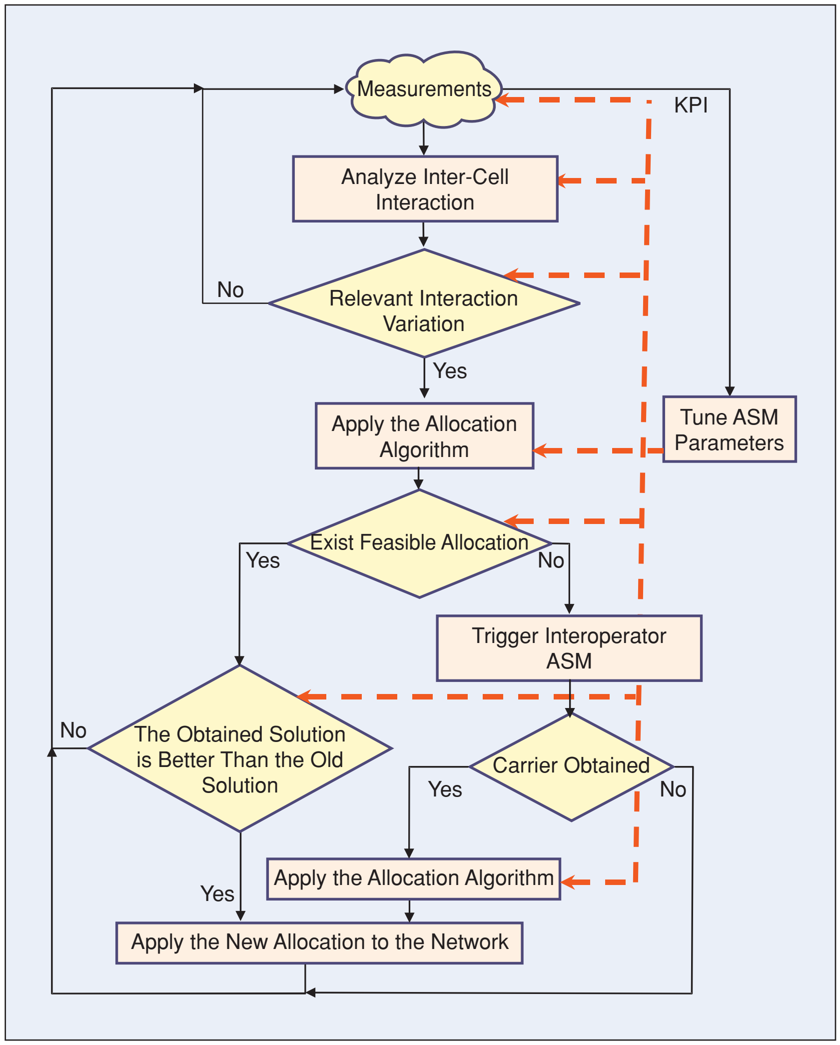

FIGURE 7 High-level vision of an intraoperator ASM algorithm.

Conclusions

This article has presented a framework where JRRM and ASM mechanisms operate synergistically toward an optimized dynamic spectrum and radio resource usage in heterogeneous wireless networks with multioperator scenarios. Given the complexity of the problem, the proposed solution follows a layered approach, where both intra and interoperator levels are considered. Thus, four strategy layers have been identified, together with the time scales at which each of them is applied. The interlayer operation has also been defined, then illustrating the dynamic operation of the presented framework.

The article has also emphasized that the solution is sustained on CN features and the intra or inter JRRM or ASM mechanisms have been integrated into the cognitive cycle. Some hints into the different stages of the cognition process have been provided, with particular attention to the decision and act phase, where specific algorithms for each layer have to be considered.

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Author Information

Oriol Sallent is Associate Professor at the Universitat Politècnica de Catalunya. His research interests are in the field of mobile communication systems, especially radio resource and spectrum management for heterogeneous networks. He has published more than 70 papers in

international journals and conferences. He has participated in several research projects of the 5th and 6th Framework Programme of the European Commission and served as a consultant for a number of private companies.

Lorenza Giupponi received the Telecommunications Engineering degree at University of Rome "La Sapienza" in July 2002 and the Ph.D. at the Department of Signal Theory and Communications (TSC) of the Universitat Politècnica de Catalunya (UPC) in May 2007. She joined the Radio communications Group of UPC in January 2003 with a grant from the Spanish Educational Ministry. From September 2006 to September 2007 she was assistant professor at UPC. In September 2007 she joined the CTTC as Director of Institutional Relations and Research Associate.

Jad Nasreddine received the B.S. degree in computer science and telecommunications in 2001 from the Lebanese University, faculty of engineering. In March 2005, he received the Ph.D. degree in computer science from the University of Rennes 1. Between April 2005 and January 2006, he was a post-doctoral researcher in the ENST Bretagne-Rennes, working on frequency management methodologies in collaboration with UPC in the framework of the European Network of Excellence (NEWCOM). In February 2006, he joined UPC as a research associate in the framework of the European FP6 project E2RII and Spanish project COSMOS. He now works in the framework of the European FP7 project E3 and Spanish project COGNOS. His research interests include cognitive and heterogeneous networks, spectrum and radio resource management, opportunistic access and cooperative networks.

Ramon Agustí received the Engineer of Telecommunications degree from the Universidad Politécnica de Madrid, Spain, in 1973, and the Ph.D. degree from UPC, Spain, 1978. In 1973 he joined the Escola Tècnica Superior d'Enginyers de Telecomunicació de Barcelona, Spain, where he became Full Professor in 1987. After graduation he was working in the field of digital communications with particular emphasis on transmission and development aspects in fixed digital radio, both radio relay and mobile communications. For the last fifteen years, he has been mainly concerned with the performance analysis, development of planning tools, and equipment for mobile communication systems, and he has published about two hundred papers in those areas. He participated in the European program COST 231 and in the COST 259 as a Spanish representative delegate. He has also participated in the RACE and ACTS European research programs and currently in the IST as well as in many private and public funded projects. He received the Catalonia Engineer of the year prize in 1998 and the Narcis Monturiol Medal issued by the Government of Catalonia in 2002 for his research contributions to the mobile communications field. He is part of the editorial board of several Scientific International Journals and since 1995 is conducting a post graduate annual course on mobile communications. He co-authored two books on Mobile communications.

Jordi Pérez-Romero is currently associate professor at the Department of Signal Theory and Communications of UPC in Barcelona, Spain. He received the Telecommunications Engineering degree and the Ph.D. from the same university in 1997 and 2001. His research interests are in the field of mobile communication systems, especially packet radio techniques, radio resource and QoS management, heterogeneous wireless networks and CNs. He has been involved in different European Projects as well as in projects for private companies. He has published papers in international journals and conferences and has co-authored one book on mobile communications.

References

[1] J.A. Hoffmeyer, "Regulatory and standardization aspects of DSA technologies—global requirements and perspectives," in *Proc. First IEEE Int. Symp. New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Baltimore, 2005, pp. 700–705.

[2] M. Buddhikot and K. Ryan, "Spectrum management in coordinated dynamic spectrum access based cellular networks," in *Proc. First IEEE Int. Symp. New Directions in Dynamic Spectrum Access Networks (DySPAN)*, Baltimore, MD, Nov. 2005, pp. 299–307.

[3] D. Bourse, R. Agusti, P. Ballon, P. Cordier, S. Delaere, B. Deschamps, D. Grandblaise, A. Lee, P. Martigne, K. Moessner, M. Muck, and O. Sallent, "The E2R II flexible spectrum management (FSM)—Framework and cognitive pilot channel (CPC) concept—Technical and business analysis and recommendations," E2R II White Paper, Nov. 2007.

[4] R.W. Thomas, L.A. DaSilva, M.V. Marathe, and K.N. Wood, "Cognitive networks," *Proc. First IEEE Int. Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Baltimore, 2005, pp. 3993–3998.

[5] D. Bourse, M. Muck, D. Bateman, S. Buljore, N. Alonistioti, K. Moessner, E. Nicollet, E. Buracchini, P. Demestichas, M . Stamatelatos, and E. Patouni, "FP6 E^{2}R Programme Achievements and Impact," SDR Forum, Invited paper, Dever, CO, 2007.

[6] G. Dimitrakopoulos, K. Moessner, C. Kloeck, D. Grandblaise, S. Gault, O. Sallent, K. Tasagkaris, P. Demestichas, "Adaptive Resource Management Platform for Future Cooperative Networks," *Mobile Networks Applicat. J.*, vol. 11, no. 6, pp. 799–811, Dec. 2006.

[7] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio," Ph.D. dissertation, Dept. Teleinformatics, Royal Institute of Technology, KTH, May 2000.

[8] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Selected Areas Commun.*, vol. 23, pp. 201–220, Feb. 2005

[9] M. Muck, S. Buljore, D. Bourse, P. Martigne, A. Lilis, E. Patouni, M. Stamatelatos, K. Tsagkaris, P. Demestichas, "Reconfigurable wireless communication systems applying distributed decision-making in a heterogeneous radio environment," in *Proc. 16th IST Mobile and Wireless Communications Summit*, Budapest, July 2007, pp. 1–5.

[10] J. Nasreddine, O. Sallent, J. Pérez-Romero, and R. Agusti, "Novel inter-cell interaction approach for WCDMA-based cognitive networks," in *Proc. IEEE Int. Conf. Communications (ICC 2007)*, Glasgow, June 2007, pp. 4573–4580.

[11] B.A. Fette, *Cognitive Radio Technology*. Amsterdam, The Netherlands: Elsevier, 2006

[12] L. Giupponi, R. Agustí, J. Pérez-Romero, and O. Sallent, "A novel approach for joint radio resource management based on fuzzy neural methodology," *IEEE Trans. Veh. Technol.*, vol. 57, pp. 1798–1805, May 2008.

[13] S. Lincke and C.S. Hood, "Load sharing versus service balancing in integrated networks," *J. Interconnection Networks*, vol. 6, no. 1, pp. 35–50, Mar. 2005.

[14] J. Pérez-Romero, O. Sallent, and R. Agusti, "A generalized framework for Multi-RAT scenarios characterisation," in *Proc. IEEE Vehicular Technology Conf. Spring*, Dublin, Ireland, May 2007, pp. 980–984.

[15] J. Pérez-Romero, O. Sallent, R. Agusti, and M. Diaz-Guerra, *Radio Resource Management Strategies in UMTS*. Hoboken, NJ: Wiley, 2005.

[16] L. Giupponi, R. Agustí, J. Pérez-Romero, and O. Sallent, "Improved revenue and radio resource usage through inter-operator joint radio resource management," *IEEE Int. Conf. Communications (ICC 2007)*, Glasgow, June 2007, pp. 5793–5800.

[17] M. Cave, C. Doyle, and W. Webb, *Essentials of Modern Spectrum Management*. Cambridge, U.K.: Cambridge Univ. Press, 2007.

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