# A Primary Spectrum Management Solution Facilitating Secondary Usage Exploitation

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**Abstract:** This paper focuses on a wireless network scenario with flexible spectrum capabilities and proposes an efficient advanced spectrum management framework that facilitates the exploitation of unused parts of the spectrum by secondary users, thus constituting a first step towards a more efficient utilisation of the spectrum. Specifically, the proposed methodology is based on the optimisation of a new metric that captures not only the spectral efficiency but also the geographical area in which spectral resources can be released for a secondary usage. As a result, the primary network operator, which is assumed to be a cellular operator, is able to determine the adequate number of carriers in each cell in accordance with the current traffic requirements and load conditions, and whenever the load conditions allow it, some carriers can be released to the secondary market. The presented results reveal that the proposed methodology, based on the new metric, is able to satisfy primary user requirements and to release unused bands in large geographical areas.

**Keywords:** Advanced Spectrum Management, Secondary spectrum access, Cellular systems.

## 1. Introduction

Wireless technologies are rapidly evolving in order to allow operators delivering more advanced multimedia services. HSPA (High Speed Packet Access) for uplink and downlink is seen as intermediate evolutionary step since the first wave of WCDMA-based (Wideband Code Division Multiple Access) networks rollout while E-UTRAN (Evolved UMTS Terrestrial Radio Access Network) is the long term perspective for 3GPP technology family. Similar paths are drawn from the 3GPP2 around the evolution of CDMA2000. Moreover, the IEEE 802 is 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. Besides, the regulatory perspective on how the spectrum should be allocated and utilized in future wireless scenarios is evolving towards a cautious introduction of more flexibility in the 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]. Then, instead of the classical fixed spectrum allocation to licensed systems and services, which may become too rigid and inefficient, the possibility to use flexible spectrum management strategies that

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dynamically allocate spectrum bands in accordance with the specific traffic needs in each area is being recently considered [2]-[4].

In this framework, several steps can be envisaged in the path towards a completely flexible use of the spectrum. One of the initial possibilities relies on the coexistence of primary and secondary spectrum usage [5][6]. Primary spectrum usage refers to the classical view in which regulators license pieces of the spectrum (i.e. frequency carriers) to specific operators in certain areas (typically at a country level), for certain periods of time (typically for several years). Operators retain then the right to use the licensed carriers by deploying the corresponding networks, which will be referred to as primary networks. This approach, although widely extended, leads to inefficiencies in the spectrum usage, because, depending on the specific spatial and temporal traffic pattern variations (e.g. daily traffic variations from business to residential areas, hot spots appearance due to specific events, etc.), not all carriers are used in practice. Consequently, a more efficient spectrum usage can be achieved if these non-used carriers are released by the primary network in specific areas and periods of time to enable other usages, which are referred to as a secondary spectrum use. This could be the case of e.g. the communication between wireless devices forming an ad-hoc network, another operator addressing a complementary market segment that uses the released carriers, etc. For instance, 802.11 hotspots could be able to increase their throughput by using released carriers by a WCDMA system when voice traffic, which is the main traffic source, drops at very late hours. In any case, in order to enable such a secondary usage, secondary users must not generate harmful interference over the primary users. In turn, it must be ensured that whenever the primary user wants to regain access to the released carriers in a certain area, all secondary transmissions making use of these carriers must be stopped. It is worth mentioning that some strategies based on primary and secondary spectrum usages are already being standardised in the IEEE 802.22 in order to utilise some non-used TV bands [7].

Under the above framework, the focus of this paper will be on primary networks transmissions, trying to develop appropriate schemes ensuring that the licensed spectrum is utilised in an efficient way in accordance with spatial traffic requirements so that some portions can be released for a secondary usage. In this way, not only secondary users can benefit from using a carrier without having to buy a license, but also the primary license holder can benefit economically from releasing some carriers that otherwise would be unused. This efficient spectrum usage can be achieved through Advanced Spectrum Management (ASM) strategies, which are responsible of the dynamic management (allocation, de-allocation, sharing) of spectrum blocks within a single or between different radio access technologies [2]-[4]. Considering a cellular system, an ASM methodology is triggered as a response to traffic changes of medium time scales (e.g. minutes or hours) affecting a specific area of the network, and it aims at ameliorating spectrum utilisation by finding the best frequency allocation to cells. For that purpose, it should be able to ask for more carriers if the traffic demand cannot be handled with the current allocated number of frequencies and, on the contrary, it should be able to release some carriers for secondary usage if the current traffic conditions can be handled with fewer carriers. Moreover, the release of carriers should be done in large geographical areas, whenever possible, so that secondary users may better exploit the resulting released carriers.

Based on the above, the objective of this paper is to present an ASM framework that accounts for the release of licensed carriers enabling a secondary usage. In particular, this will involve the introduction of a new metric reflecting the ability of a given strategy with respect to the release of carriers in a large geographical area, and the development of specific algorithms taking into account this metric. The remaining of the paper is organised as follows. Section 2 presents the overall ASM methodology for a cellular system, including the new metric. Section 3 particularises the framework for the uplink of a

WCDMA system and presents a simulated annealing-based allocation algorithm, which is evaluated by means of simulations in Section 4. Finally Section 5 summarises conclusions.

## 2. ASM Methodology

The objective of a wireless network operator is to make a deployment that satisfies some coverage and quality targets in an as high as possible profitable way. That is, network operator intends to get maximum revenue out of the deployed infrastructure and the gained spectrum usage rights. Therefore, network operators are interested in mechanisms that maximize the utilization of the available radio resources, which are the result of the deployed sites and allocated carriers per cell in a given area. Ideally, the amount of radio resources at a given time and place should match the traffic demand. However, this is not possible in practice with a fixed site deployment and spectrum allocation, since the high level of dynamism associated to traffic demand leads to mismatches between offered and requested radio resources. Then, focusing on time scales ranging from minutes to hours and assuming that, on the one hand, the site deployment is fixed and, on the other hand, proper short-term radio resource management strategies are operating, ASM will be the technique enabling the necessary flexibility to achieve the best possible matching between offered and required spectrum resources by adding or removing carriers to/from cells in accordance with user density, connection establishment generation processes, service type and environment characteristics. In turn, the observation that some user satisfaction and/or network performance metrics are degraded compared to some reference values can be taken as trigger event for the case that the current amount of spectrum resources should be increased while, on the contrary, the observation that these metrics are enhanced compared to some reference values can be taken as trigger event for the release of some carriers.

In the following, the general operation of an ASM algorithm for a cellular network accounting for the above considerations is introduced. We assume that there are $F$ carriers available and define a spectrum allocation as $A=\{\Lambda^{(1)}, \Lambda^{(2)}, ..., \Lambda^{(F)}\}$ where $\Lambda^{(f)}$ is the set of cells using carrier $f$. The objective of the ASM methodology is then to determine the allocation $A$ so that, on the one hand, the requested traffic is handled with the minimum number of carriers and, on the other hand, carriers are released in large geographical areas whenever possible. The latter condition ensures a better profitability of the released spectrum for a secondary market, which will turn in a higher willingness of the secondary network to rent the released carriers thus increasing the incomes for the primary operator.

With the above objectives in mind, it is necessary to define appropriate metrics capturing the two objectives, namely the degree of satisfaction of primary users with the current spectrum allocation and the geographical area considerations for the released spectrum. For the former, multiple types of Quality of Service (QoS) Key Performance Indicators (KPIs) can be retained reflecting both service performance (e.g. throughput, delay, etc.) and accessibility (e.g. blocking, dropping, etc.). For the latter, indicators related with spectrum efficiency can be considered including geographical considerations.

Usually, Spectrum Efficiency (SE) is defined as the throughput per spectrum bandwidth and surface units for a given infrastructure deployment, so that it can show how efficient a given allocation is, when using a certain bandwidth. Similarly, in [9] the Spectrum Opportunity Index (SOI) is introduced as a metric that accounts for the average spectrum that has been released in a certain area. In order to capture the size of the geographical areas where the spectrum is being released as an indication of the profitability for the potential secondary usage, in this paper a novel metric, the Useful Released Surface (URS), denoted as $u$, is proposed. For a certain frequency allocation, it is defined as:

$$u = \sum_{f=1}^{F} W^{(f)} \sum_{c=1}^{C^{(f)}} S_c^{(f)} \omega_c^{(f)} \quad (1)$$

where $W^{(f)}$ is the bandwidth of carrier $f$, $C^{(f)}$ is the set of non-contiguous areas where the carrier $f$ could be used by a secondary network, $S_c^{(f)}$ is the surface of the area $c$ in relation with carrier $f$ and $\omega_c^{(f)}$ is the weight given to this area depending on the expected number of secondary users in this area to account for the fact that the release of carriers will be more effective in areas with a significant number of potential secondary users. The area where a given carrier can be utilised for a secondary transmitter (i.e. white areas in the example of Figure 1) depends, not only on the specific frequency allocation (i.e. in which cells, carrier $f$ is allocated to the primary users, depicted in black in Figure 1) but also on the protection zone (depicted in grey in Figure 1) that should be left around these cells in order to ensure that the interference level induced by the secondary users to primary users does not exceed the maximum allowed level. This protection zone should be determined based on the acceptable interference level by the primary network, the estimated maximum transmitted power by the secondary transmitters and the propagation conditions.


*Figure 1: Illustration of the area where a certain carrier can be released*

In the last few years, several ASM methods have been proposed. These methods mainly differ by the used metrics to reflect system performance at cell level or by the allocation algorithms. Some of these methods use traffic estimators to predict the needed number of carriers without a efficient representation of interference [10]. Other methods consider inter-cell interference as a directly proportional function to intra-cell interference with a constant, which can lead to under or over estimation of inter-cell interference resulting in probably non-suitable allocation. Therefore, this contribution involves the introduction of simulated annealing-based ASM algorithm using coupling matrix properties that are able to reflect inter-cell interactions with more precision [8].

A generic flow diagram of the proposed ASM framework is presented in Figure 2. First, the information from radio measurements is collected to detect substantial variations in the scenario in terms of load level and spatial traffic distribution, which are reflected by modifications in inter-cell interactions. For that purpose, metrics able to capture such interactions are required. An example is the coupling matrix concept defined in [8], whose elements represent the average values of parameters that reflect the impact of one cell on another. By analysing these inter-cell interactions, it is possible to detect the relevant variations in the scenario and trigger the allocation algorithm, as depicted in Figure 2, in order to determine if either more carriers are required in some cells (e.g. the traffic load has increased and it can no longer be served with the current number of carriers) or if some carriers can be released (e.g. the traffic load has decreased and it can be served with fewer carriers). Thereafter, the allocation algorithm decides the frequency allocation in accordance with the maximization of $u$ subject to a set of constraints in terms of vector $\mathbf{\Psi}$ of QoS KPIs to be ensured (e.g. maximum outage probability, minimum throughput, etc.) and a set of access technology considerations (e.g. maximum transmitted power, sensitivity, etc.) for the current number of carriers. If no carrier allocation satisfies vector $\mathbf{\Psi}$ the optimization problem does not have a feasible solution and the new allocation $A_n$ at the output of the algorithm will be empty. This means that with the actual number of carriers the system will not be able to handle the traffic with the specified QoS requirements. In this case, the ASM can try to obtain more carriers, e.g. by requesting them to the regulator or to another operator that has released them for a secondary usage. If this step fails, the ASM keeps the old allocation $A_o$. In turn, if a new carrier is obtained, the allocation algorithm will be executed again. In case that the algorithm provides a feasible allocation (i.e. the new allocation $A_n$ at the output of the algorithm is not empty), meaning that requirements $\boldsymbol{\Psi}$ can be fulfilled, the ASM tests if the new allocation has better URS than the actual allocation (i.e. if $u(A_n) > u(A_o)$). If so, the new allocation is applied to the network and the unused carriers can be put in secondary market in specific areas in accordance with the protection zone. Otherwise, the ASM stops and keeps the previous frequency allocation $A_o$.

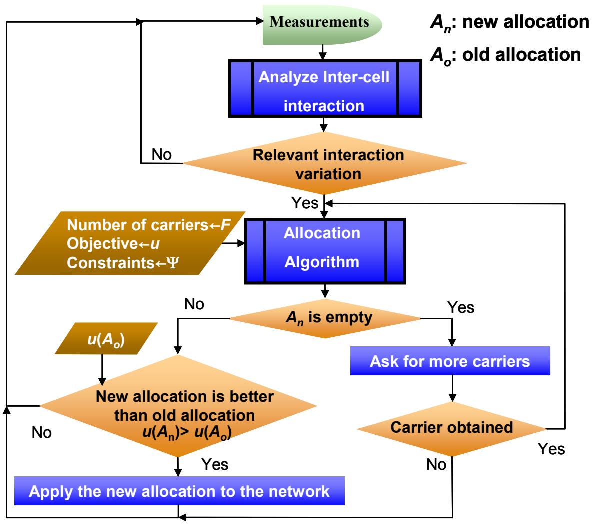


*Figure 2: High level vision of an ASM algorithm*

## 3. Case study: WCDMA scenario

This section presents a particular allocation algorithm for the general ASM framework presented in Figure 2 assuming a WCDMA scenario with $F$ carriers per operator, and considering a network with $K$ cells.

### *3.1. Detecting Relevant Interaction Variations*

As for the inter-cell interaction detection phase in Figure 2, the coupling matrix is considered as defined in [8]. This is built based on path loss measurements and $E_b/N_o$ requirements from the different terminals. A relevant interaction variation is detected based on two conditions: (1) the measured percentage of users not reaching $E_b/N_o$ requirements is higher than a given threshold in at least one cell, (2) the difference between $r$ elements of the coupling matrices in two observation periods is higher than a given threshold.

### *3.2. Allocation Algorithm*

The optimization problem to be solved by the allocation problem is an NP-hard problem and therefore, meta-heuristic algorithms are suitable to find good solutions. To this end, we propose a simulated annealing (SA)-based algorithm, using the same functions of the algorithm presented in [11]. However, in this case the objective function for the new algorithm is to maximize the URS instead of the spectrum efficiency, and thus the algorithm will be referred to as SA-URS. The only QoS KPI constraint is that the maximum outage probability over all cells should be lower than a given threshold while the constraints related to the access technology include the fact that the transmitted power should be below a maximum level and the number of carriers allocated to each cell should be lower than $F$. The outage probability and the transmitted powers are also estimated using the same method as in [11]. The algorithm starts by assigning to each cell $j$ the necessary number of carriers $F_{j,\min}$ that enables it to handle its internal load. After this initial computation, if at least one cell requires more than the available number of carriers $F$, the algorithm stops and generates an output with an empty set $A_n$. Otherwise, the SA loop starts. The fundamental idea of the SA loop is to allow moves that lead to worse quality than the current solution with a time-decreasing probability in order to escape from local minima. The solution space where the SA algorithm searches a solution is defined by the allocations that satisfy the lower-bound limit $F_{j,\min}$ and the upper-bound limit $F$ on the number of allocated carriers. The SA starts from a random allocation using the initial number of allocated carriers to each cell $F_{j,\min}$. Then, the URS and the QoS KPI constraints of the actual allocation are compared to the previous values. The algorithm adopts the new allocation if its URS is higher than the previous one and the constraints are satisfied. Otherwise, the old allocation is recovered with a certain probability that increases with the number of iterations. From the adopted allocation, the algorithm chooses randomly an allocation by adding or eliminating one carrier to a cell. At each iteration, the URS is compared to a saved value, which is initiated to 0. If the actual value is higher than the saved one, the actual allocation is considered as a temporary optimal allocation. More details on the SA-based algorithm could be found in [11]. All needed information ($E_b/N_o$, long-term path losses, etc.) for the computation of the coupling matrices can be obtained using the measurements collected either by cells or mobiles in an operative network.

## 4. Results

The SA-URS algorithm has been evaluated in a system with 61 macro-cells and $F$=3 carriers as depicted in Figure 3. The simulation parameters are summarized in Table 1. The allocation algorithm is compared to the uniform algorithm where the necessary number of carriers is found in order to satisfy the outage constraint considering that all cells are using the same number of carriers. Moreover, it is compared to the SA-based algorithm (SA-SE) of [11] where the objective is to maximize the spectrum efficiency.

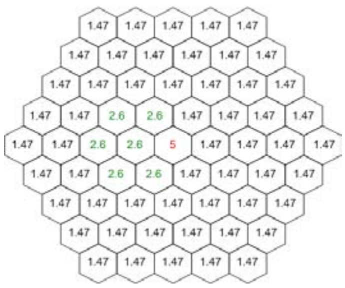


*Figure 3: Simulation layout (numbers inside cells are the percentage of users in each cell in respect to the total number of users)*

The maximum outage probability over all cells is plotted in Figure 4 (left) as a function of the total number of users in the system. It can be seen that the three algorithms satisfy the outage threshold of 0.05 and that the uniform allocation has the lowest outage due to the fact that all carriers are used in each cell. Correspondingly, the uniform allocation presents the lowest spectrum efficiency, as depicted in Figure 4 (right). In turn, both SA-SE and SA-URS exhibit a higher value of spectrum efficiency, being it slightly higher for SA-SE because its objective is the optimisation of this parameter. Figure 5 (left) plots the percentage of unused spectrum which is given by the average number of unused carriers per cell (i.e. this would be a similar measure as the SOI from [9]) and Figure 5 (right) presents

*Table 1: Simulation Parameters*

| | |
|---|---|
| Cell radius | 1 km |
| Path loss model | 128.1+37.6×$\log_{10}d$ (Km) |
| Background noise power | -103 dBm |
| Maximum allowed power | 21 dBm |
| Transmitted power range | 61 dB |
| $E_b/N_0$ target | 3 dB |
| Spreading factor Θ | 23 dB |
| Shadowing factor deviation | 7 dB |
| Shadowing factor cross-correlation | 0.5 |
| Power control | Perfect power control |
| Outage threshold | 0.05 |

the corresponding URS. It is assumed that the protection zone of a given cell corresponds to the six adjacent cells. Moreover, the value of weight $\omega_c^{(f)}$ in (1) corresponds to the fraction of secondary users in area $c$ assuming that they are uniformly distributed in the whole system. It can be observed in Figure 5 that for the uniform allocation both the URS and the percentage of unused spectrum are null, because with this approach it is not possible to reduce the outage probability below the threshold of 0.05 with less than 3 carriers. The SA-SE algorithm has slightly better performance than the SA-URS in terms of percentage of unused spectrum, mainly because the former tries to increase the spectrum efficiency, thus reducing the number of carriers in some cells. However, as it is shown in Figure 5 (right), the URS is much higher with the proposed algorithm, meaning that it allows a more efficient secondary spectrum use. Finally, Figure 6 plots the released areas for the first two carriers when using the two allocation algorithms for a specific load condition. As for the third carrier, it is not shown because for the two algorithms it is obtained that it cannot be released anywhere. The figure shows that the contiguous areas released by the SA-URS are significantly greater than the contiguous areas released by the SA-SE.

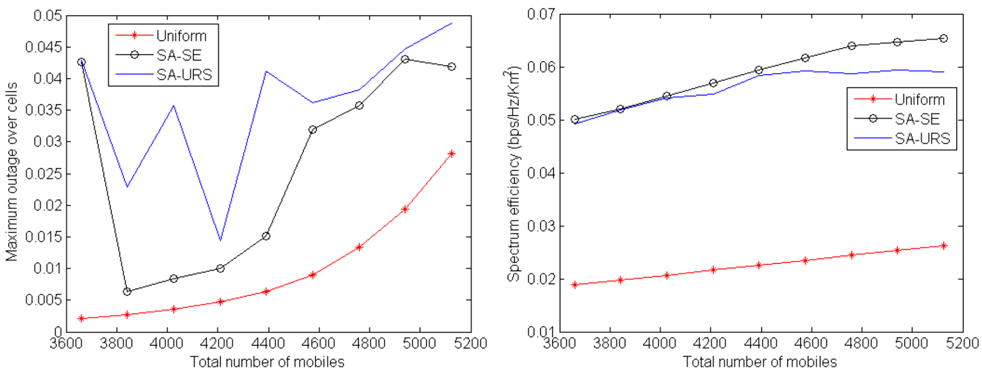


*Figure 4: Outage probability (left) and spectrum efficiency (right) as a function of the total number of users*

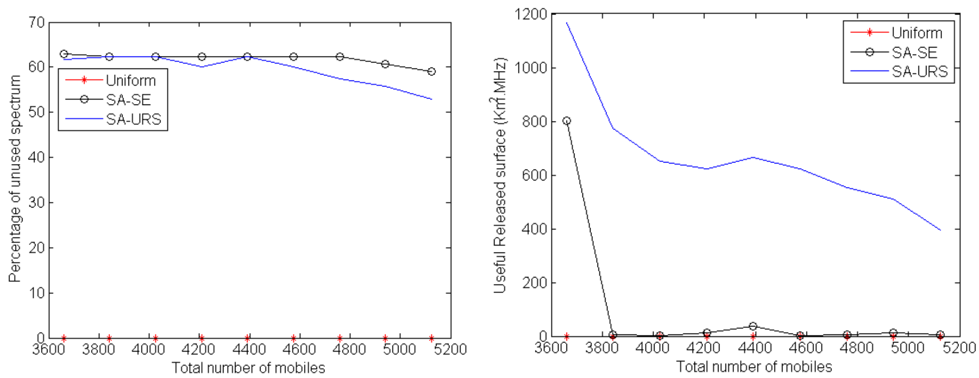


*Figure 5: Percentage of unused spectrum (left) and URS (right) as a function of the total number of users*

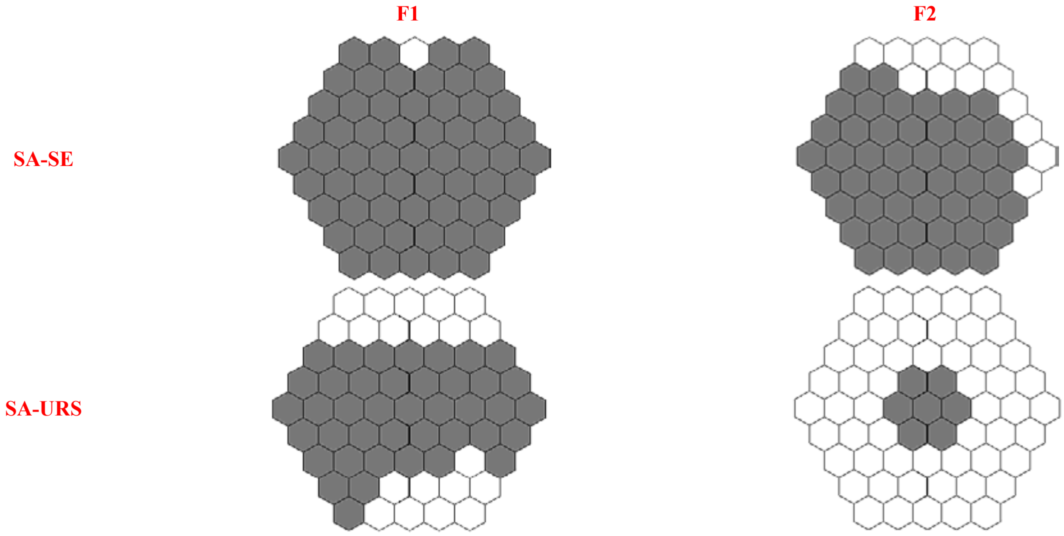


*Figure 6: Released areas (in white) for carriers F1 and F2 using the SA-SE and the SA-URS allocation algorithms for a traffic of 4400 mobiles*

## 5. Conclusions

This paper has presented a new spectrum management methodology developed with the target of achieving, on the one hand, an efficient spectrum utilisation of the spectrum bands that are owned by a cellular primary network operator, in accordance with the existing load levels and, on the other hand, when the load levels are low enough, it allows releasing some carriers for a secondary usage in large geographical areas. It is based on a simulated annealing approach that maximises a new metric accounting for the geographical area in which each carrier is released. Simulation results have shown that the proposed method gives the best results in terms of released carriers in large areas. Future work includes the detailed study of the protection zones to be left in accordance with primary and secondary user characteristics.

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