Published in IET Communications
Received on 28th September 2007
Revised on 12th February 2008
doi: 10.1049/iet-com:20070497

In Special Issue on Cognitive Spectrum Access

ISSN 1751-8628

Advanced spectrum management in wideband code division multiple access systems enabling cognitive radio usage

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Abstract: The authors propose a new advanced spectrum management (ASM) methodology for wideband code division multiple access systems based on the concept of coupling matrix, which is able to capture inter-cell interactions. The proposed methodology takes into account the fact that each cell can be associated to more than one carrier and aims at liberating some carriers in large geographical zones, so that they could eventually be used by, for example, secondary cognitive radio users that exploit the flexible frequency allocation and opportunistic spectrum access. Simulation results show that the proposed methodology increases spectrum efficiency while guaranteeing the requested QoS levels. Moreover, a new metric has been introduced to reflect the capability of the ASM methodology to liberate some carriers in large geographic zones. This metric has been used to compare the different approaches presented here.

1 Introduction

Traditionally, cellular networks have been using fixed spectrum allocation paradigms based on fixed traffic distribution estimations. For instance, fixed frequency reuse patterns have been adopted for global system for mobile communications networks, whereas wideband code division multiple access (WCDMA) systems generally apply a frequency reuse of one with some exceptions, such as the case of hierarchical cell structures where different carriers are assigned to different cells (e.g. macro and micro-cells) or different services [1]. However, one key issue in wireless networks is that traffic distribution is time/space dependent and subject to regular changes on the one hand and unexpected changes on the other hand. Regular traffic changes have a rather fixed switching point from one traffic distribution to another and key information about these changes can be predicted during planning phase (e.g. hotspots are mainly concentrated in business areas during the day and in residential areas in the evening). In addition to these predictable patterns, other unexpected traffic changes could occur at any time. Depending on the nature of these changes, inter-cell interactions can be significantly altered leading to indispensable modification in the frequency allocation to cells. Therefore traditional fixed frequency allocation methodologies do not match with the changing traffic distribution within all time periods, leading to cases where a large swath of the spectrum is underutilised at a given period, whereas another swath suffers congestion. Hence, spectrum access and not spectrum scarcity reduces spectrum efficiency as stated by the Federal Communications Commission [2, 3].

In order to adapt the frequency allocation to traffic distribution, a new paradigm of advanced spectrum management (ASM) methodologies should be developed. The new paradigm should exploit all degrees of flexibility existing in composite beyond 3G networks; that is, the allocation of carriers to cells, radio access technologies (RAT) and operators should be considered paving the way to free-for-all spectrum access with opportunistic spectrum usage [4].

ASM methodologies concern traffic changes from medium to long time scales (e.g. minutes, hours or days) that affect a specific area of the network. For a given

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system, they aim at ameliorating spectrum efficiency by finding the best frequency allocation to cells. Moreover, they should be able to detect the limits of the network to support existing traffic with its allocated carriers. On the one hand, ASM methodologies should be able to ask for more carriers if the required number of carriers is higher than the actual number of carriers associated to the system. On the other hand, ASM methodologies should be able to put some carriers in a secondary market (e.g. for opportunistic radio usage) if the required number of carriers is lower than the actual number of carriers in order to efficiently utilise these scarce and expensive resources. In summary, the ASM methodology should guarantee:

- a better spectrum utilisation that can be achieved, thanks to the fact that the network will use the minimum number of carriers;

- carrier pools in large geographical areas that can be released so that cognitive radio users may exploit a true flexible frequency allocation, including opportunistic access to the spectrum in a beyond 3G composite scenario [5, 6].

Therefore the ASM methodology aims at finding the minimum global number of carriers needed by a system, the minimum number of carriers needed by each cell and the best mobile distribution over carriers that satisfies operator policies. These objectives should be reached while QoS levels of the served users are kept at the requested level.

The last few years have witnessed a fast pace in the development of ASM methodologies exploiting the new degrees of flexibility introduced by the emerging vision of regulatory bodies about spectrum pooling and sharing in composite networks where different RATs and different operators coexist [4–17]. These methodologies use some metrics that reflect system performance at cell level as inputs for optimisation algorithms such as local search or genetic algorithms in order to find a spectrum allocation as close as possible to the optimum allocation. Some of these methodologies use traffic estimators to predict cell loads which are used afterwards to allocate carriers [12]. However, this approach only considers in a simplified way inter-cell interference that has high impact on cell capacity especially in interference limited systems such as WCDMA. Recently, new approaches were proposed and considered inter-cell interference as a directly proportional function to intra-cell interference with a constant f [18]. However, the value of f is highly dependent on the spectrum allocation. Thus, the inter-cell interference could be estimated wrongly leading to probably non-suitable allocation.

In this paper, we formulate the problem of finding efficient frequency allocation in the uplink of a WCDMA network with multiple available carriers as a step forward towards a generic ASM methodology for composite networks. The proposed methodology is based on the so-called coupling matrix [19, 20] that is able to reflect inter-cell interactions using measurable parameters. The proposed methodology could be integrated in the planning tool to find an efficient frequency allocation corresponding to periodic traffic changes and it could also be used to dynamically change the frequency allocation in the context of cognitive networks using appropriate triggering events (e.g. QoS indicators etc.) as it was indicated in [20]. Previous works of the authors in [19–21] considered the situation in which only one carrier per cell was allocated. In this paper, the previous work is extended to account for the more general situation in which several carriers per cell can be allocated depending on the specific traffic demands. Furthermore, an ASM methodology is developed from the perspective of releasing significant pieces of spectrum in large geographical areas so that they can be used by cognitive radios.

The remaining of this paper is organised as follows. First, we introduce the coupling matrix in Section 2. The coupling matrix is used in Section 3 in order to develop a new ASM methodology that enables the system to estimate the number of needed carriers and to locally saving some of these carriers (i.e. in some geographical zones). Then, the performance of the proposed methodology is studied in Section 4. Finally, we conclude with useful remarks.

2 Coupling matrix

We consider a WCDMA system with K cells and F carriers reflecting that operators use to have more than one frequency carrier in current WCDMA systems. The set of all cells is called $\Lambda = \{i: j \in \{1, 2, \ldots, K\}\}$ and the set of all used carriers is called $\Phi = \{f: f \in \{1, 2, \ldots, F\}\}$. All used index notations are summarised in Table 1.

Coupling matrix has been introduced in [19] and is computed by assessing relationships between the total received interferences from different cells in uplink using E_b/N_o definition

$$\left(\frac{E_b}{N_o}\right)_{i_j} = \frac{P_{j,i_j}\Theta_{i_j}}{\sum_{k_j=1}^{n_j} P_{j,k_j} - P_{j,i_j} + \chi_j + N_T} \tag{1}$$

where i_j is the ith user of the jth cell, Θ_{i_j} the spreading factor of mobile i_j, P_{j,i_j} the useful received power by cell j from mobile i_j, χ_j represents the inter-cell interference experienced by mobile i_j, n_j the number of users in cell j and N_T the background noise power.

Moreover, we denote by I_j the total power received by cell j

$$I_j = \chi_j + \sum_{k_j=1}^{n_j} P_{j,k_j} + N_T \tag{2}$$

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Table 1 Index notation

Indices	Signification
F	The global number of carriers
F_{av}	The number of available carriers
F_j	The number of carriers allocated to cell j
Φ	The set of all carriers
Φ_j	The set of carriers allocated to cell j
K	The number of cells
Λ	The set of all cells
Λ_f	The set of cells using carrier f
i_j	The ith user of the jth cell
ϑ_j	The set of users connected to cell j
n_j	The number of users connected to cell j
Θ_{i_j}	The spreading factor of mobile i_j
Θ	The spreading factor of the provided service
P_{j,i_j}	The useful received power by cell j from mobile i_j
χ_j	The inter-cell interference experienced by mobile i_j
I_j	The total received power by cell j
$\boldsymbol{I}^{(f)}$	The vector of total power received powers by cell j in carrier f
N_T	The background noise power
$\boldsymbol{P}_N$	The $K \times 1$ noise vector
$\boldsymbol{P}_N^{(f)}$	The noise vector in carrier f
$L_{i_l,j}$	The total path loss including antenna gains of mobile i_l towards cell j
$S_{j,l}$	The impact of users of cell j on cell l
$S_{j,l}^{(f)}$	The impact of users of cell j on cell l in carrier f
$\boldsymbol{C}$	The global coupling matrix
$\boldsymbol{C}^{(f)}$	The associated matrix to carrier f
$\rho(\boldsymbol{C})$	The spectral radius of matrix $\boldsymbol{C}$
$\mathcal{M}_f$	The mapping between cell indices and matrix indices in carrier f
$\mathrm{Pr}_{o,j}$	The long term outage probability in cell j
δ	The outage probability threshold
υ	The spectrum efficiency
R_b	Bit rate of the provided service
P_{max}	The maximum allowed power by given user

It was shown in [19] that vector $\boldsymbol{I} = (I_1, I_2, \ldots, I_K)^T$ satisfying E_b/N_o constraints can be written in the following matrix form for a given carrier

$$\boldsymbol{I} = \boldsymbol{C}\boldsymbol{I} + \boldsymbol{P}_N \tag{3}$$

where $\boldsymbol{P}_N$ and $\boldsymbol{C}$ are, respectively, the $K \times 1$ noise vector and the $K \times K$ coupling matrix defined by

$$P_{N,j} = \frac{N_T}{1 - S_{j,j}} \tag{4}$$

$$C_{j,l} = \begin{cases} 0 & \text{if } l = j \\ \frac{S_{l,j}}{1 - S_{j,j}} & \text{otherwise} \end{cases} \tag{5}$$

where $S_{l,j}$ is the impact of users in cell l on cell j and defined by

$$S_{l,j} = \sum_{i_l=1}^{n_l} \frac{L_{i_l,l}}{L_{i_l,j}} \frac{1}{(\Theta_{i_l}/(E_b/N_o)_{i_l}) + 1} \tag{6}$$

where $L_{i_l,j}$ is the total path loss including antenna gains of mobile i_l towards cell j. Each element of coupling matrix $\boldsymbol{C}$ represents the variation of the total power received in uplink by one cell as a response to the variation in the total power received by another cell [19]. It is worth mentioning that the formulation of coupling matrix elements in (5) is generic to account for the coexistence of multiple services in the scenario, simply by considering the corresponding spreading factor and E_b/N_o requirements of each service in the computation of (6).

Matrix $\boldsymbol{C}$ has interesting properties that can be used in the ASM methodology. In [19], we have shown that a non-constrained system (i.e. a system without power limitation) is able to serve all users with the required E_b/N_o using finite positive powers if and only if the spectral radius $\rho(\boldsymbol{C})$ of the corresponding coupling matrix $\boldsymbol{C}$ (i.e. the eigenvalue with the maximum modulus) is strictly less than unity. When power constraints are added, the value of the spectral radius should be much lower than unity. Therefore the spectral radius could be considered as a first constraint to system feasibility since it has a paramount impact on the interference and transmitted power patterns and thus on system performance.

In a system with several carriers, a coupling matrix is associated to each carrier. The associated matrix to carrier f is called $\boldsymbol{C}^{(f)}$ and includes only the elements corresponding to cells that are associated to carrier f (i.e. they belong to set Λ_f). Therefore different carriers will have generally coupling matrices with different sizes. In order to map the cell indices of the global coupling matrix $\boldsymbol{C}$ to the indices of matrix elements in the different carriers, we define the set of mapping functions $\mathcal{M}_f$

$$\mathcal{M}_f(j) = j - K_{f,j} \tag{7}$$

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where $K_{f,j}$ is the number of cells that are not associated to carrier f and have a smaller index than j

$$K_{f,j} = |\{l \in \Lambda - \Lambda_f : l < j\}| \tag{8}$$

where $|\cdot|$ is the cardinality of a set. Therefore the corresponding element reflecting the interaction between cell j and l in $\boldsymbol{C}^{(f)}$ is $C^{(f)}_{\mathcal{M}_f(j),\mathcal{M}_f(l)}$ and is computed using the value of $C_{j,l}$ of matrix $\boldsymbol{C}$.

In this contribution, we consider that users are uniformly distributed over carriers in a cell reflecting a load balancing strategy (i.e. the same load is kept in all carriers). Therefore the value of factors $S^{(f)}_{j,l}$ corresponding to carrier f could be written as

$$S^{(f)}_{j,l} = \frac{S_{\mathcal{M}_f^{-1}(j),\mathcal{M}_f^{-1}(l)}}{F_{\mathcal{M}_f^{-1}(j)}} \tag{9}$$

Then, the corresponding element of the coupling matrix $\boldsymbol{C}^{(f)}$ is estimated using (5) and (9)

$$C^{(f)}_{j,l} = \frac{S_{\mathcal{M}_f^{-1}(l),\mathcal{M}_f^{-1}(j)}/F_{\mathcal{M}_f^{-1}(l)}}{1 - (S_{\mathcal{M}_f^{-1}(j),\mathcal{M}_f^{-1}(j)}/F_{\mathcal{M}_f^{-1}(j)})} \tag{10}$$

and the noise vector element corresponding to carrier f is also estimated using (4) and (9)

$$P^{(f)}_{\mathrm{N},j} = \frac{N_{\mathrm{T}}}{1 - (S_{\mathcal{M}_f^{-1}(j),\mathcal{M}_f^{-1}(j)}/F_{\mathcal{M}_f^{-1}(j)})} \tag{11}$$

3 Intra-RAT ASM

3.1 Problem formulation

Frequency allocations should satisfy QoS requirements that could be reflected by user satisfaction metrics. In general, a user is considered satisfied if its measured $E_{\mathrm{b}}/N_{\mathrm{o}}$ is higher than a given threshold, which in turn is related to certain bit error rate or delay requirements [22]. The outage probability is then defined as the fraction of users not achieving the desired $E_{\mathrm{b}}/N_{\mathrm{o}}$ threshold. In this contribution, we use the outage probability at cell level and more specifically the maximum outage probability over all cells reflecting the intention of operators to locally minimise the outage probability. This can prevent the presence of islands of cells with high probability while the total outage probability is acceptable. We emphasise here that the proposed methodologies can be easily adapted to other operator's metrics such as the average outage probability or the outage probability of specific services. Frequency allocations should also meet operator strategies concerning the trade-off between carrier distribution over the covered area and QoS levels. For instance, an operator may prefer to have some free carriers in some zones at the expense of a slight decrease in QoS levels for economical reasons (e.g. to allocate one carrier to secondary market or to rent it to another operator in a large area) or may simply aim at increasing spectrum efficiency. The spectrum efficiency when only one service is provided by the operator is defined as the cell throughput per unit of bandwidth and is given by

$$\nu = R_{\mathrm{b}} \frac{1}{KW} \sum_{j \in \Lambda} \frac{(1 - \mathrm{Pr}_{\mathrm{o},j}) n_j}{F_j} \tag{12}$$

where W is the transmission bandwidth of one WCDMA carrier, R_{b} the bit rate of the provided service and $\mathrm{Pr}_{\mathrm{o},j}$ the estimation of the outage probability in cell j.

Therefore ASM methodologies aims at finding the best frequency allocation to cells (i.e. sets Λ_f) that maximises the spectrum efficiency and it is expressed by the following optimisation problem

$$\begin{aligned} &\text{Maximise} \quad \nu \\ &\text{Subject to} \quad \max_{j \in \Lambda} \ \mathrm{Pr}_{\mathrm{o},j} < \delta \\ &\qquad\qquad P_{\mathrm{T},i_j} \le P_{\max} \quad \forall i_j \in \vartheta_j, \quad j \in \Lambda \end{aligned} \tag{13}$$

where $\mathrm{Pr}_{\mathrm{o},j}$ is the outage probability in cell j, δ the outage probability threshold at cell level, $P_{\max}$ the maximum available power at the terminal of user i_j, ϑ_j the set of users in cell j and P_{T,i_j} the transmitted power by terminal i_j.

3.2 Methodology inputs and outputs

Herein, we introduce the different inputs and we specify the considered values for the proposed methodology. Two types of inputs are defined: system inputs and operator policies.

System inputs are:

- number of available carriers F_{av};
- network deployment: defined by the number and location of cells;
- traffic distribution: defined by the user density in each region;
- user characteristics: spreading factor and required $E_{\mathrm{b}}/N_{\mathrm{o}}$ for each service, path loss distribution etc.

Operator policies are:

- *Strategy to allocate mobiles to carriers in a cell*: We assume that the operator follows a load balancing approach, so that the same load is kept in all carriers of a given cell. This is the simplest distribution, but more complicated approaches could be developed and used as an input. This input is necessary for the computation of the coupling matrices associated to the different carriers.
- *Network performance indicator (i.e. outage probability at system level or cell level)*: We consider in this paper the

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outage probability at cell level, specifically the maximum outage over cells.

• *Network thresholds corresponding to the performance indicator*: We consider in this paper a threshold $\delta = 0.05$ that the outage probability at cell level should not exceed.

Using the above inputs, the ASM methodology provides the following outputs.

• The number of carrier F_j required by cell j for all cells in the considered network.

• The set Λ_f of cells associated to carrier f for all required carriers.

• The global number of carriers F required by the system.

From these outputs, we can estimate:

• The needed $F_j - F_{\text{av}}$ carriers that should be rented/bought in order to support a certain traffic increase in cell j when F_j is higher than F_{av}.

• The non-used $F_{\text{av}} - F_j$ carriers that can be put in a secondary market when F_j is lower than F_{av} in cell j.

3.3 ASM methodology steps

Since the outage probability is a nonlinear function, the frequency allocation problem defined in (13) is a combinatorial problem with nonlinear constraints which is known to be an NP-hard problem [23]. Therefore we introduce simple heuristic ASM methodologies that use a closed loop to allocate carriers to cells aiming to reach the objective while satisfying the constraints defined in (13).

The ASM methodology is depicted in the block diagram shown in Fig. 1. The algorithm starts in step 1 by estimating global coupling matrix $\boldsymbol{C}$ and noise power $\boldsymbol{P}_{\text{N}}$ by using (4)–(6) based on measurements and/or outputs from a planning tool.

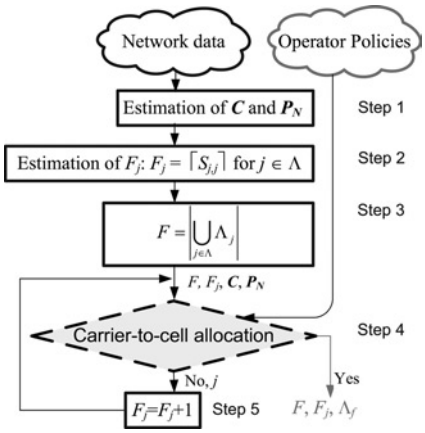

Figure 1 *Block diagram of the proposed ASM methodology*

Step 2 involves the first estimation of the number of carriers to be allocated to each cell. In cell j, the required number of carriers should be sufficient to handle at least the load coming from intra-cell users, which corresponds to the term $S^{(f)}_{\mathcal{M}_f(j),\mathcal{M}_f(j)}$. This means that the following condition should be fulfilled [24]

$$S^{(f)}_{\mathcal{M}_f(j),\mathcal{M}_f(j)} < 1 \quad \forall j \in \Lambda \tag{14}$$

By combining (9) and (14), the estimation of the number of carriers F_j for cell j is first initiated using the following equation to overcome intra-cell interference

$$F_j = \lceil S_{j,j} \rceil \tag{15}$$

where $\lceil S_{j,j} \rceil$ is the first integer higher than or equal to $S_{i,j}$.

In step 3, the algorithm estimates the global number of carriers F from the number of carriers required per cell

$$F = \max_{j \in \Lambda} (F_j) \tag{16}$$

In step 4, the algorithm allocates the needed carriers to cells based on the carrier-to-cell allocation policy explained in Section 3.5. Within the carrier-to-cell allocation block, a feasibility test is executed in order to guarantee QoS levels as detailed in Section 3.4.

In step 5, if the system is not feasible (i.e. the QoS requirements defined by the network are not satisfied), a new carrier is added to the 'worst cell' provided by the carrier-to-cell allocation block. Otherwise, the algorithm will end with an output including the global number of carriers F, the number F_j of carriers allocated to cell j and sets Λ_f.

It should be noted that the proposed methodology is applied over medium and long-term periods (e.g. minutes, hours, half a day etc.) and the elements of the matrix are estimated from the expected averaged values. Therefore the fast fluctuation (because of mobility, fast fading etc.) is averaged and does not have important impact on the accuracy of the matrix. Also, for the same reason, the proposed methodology does not put significant computation constraints because of scalability since computations are only required at the rather slow medium/long-term traffic pattern variability. Moreover, all needed information ($E_{\text{b}}/N_{\text{o}}$, long-term path losses, spreading factors) for the computation of the coupling matrices can be obtained using the measurements collected either by cells or mobiles in operative networks.

3.4 Feasibility test

In order to satisfy QoS requirements, the operator should specify a feasibility test and the corresponding thresholds.

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The feasibility test is shown in Fig. 2 and is based on estimating the maximum outage probability. Outage estimation is relevant for the ASM methodology, since it estimates the real performance of the frequency allocation algorithms without testing them on real systems, which could lead to unacceptable performance for significant periods of time.

If we assume that all users require the same service with E_b/N_o and spreading factor ε and Θ, respectively, the outage probability can be written as

$$\Pr_{o,j} = 1 - \mathrm{cdf}_j\left(\frac{(\Theta/\varepsilon)+1}{I_j} P_{\max}\right) \tag{17}$$

where I_j is the estimated value of the received power using (3) and cdf_j the cumulative distribution function of mobile path losses served by cell j. This estimation could be easily found from E_b/N_o equation with some simple mathematical manipulation. In case that cell j has several carriers, its outage probability is given by

$$\Pr_{o,j} = \frac{\sum_{f\in\Phi_j} \Pr_{o,j}^{(f)} n_j^{(f)}}{n_j} \tag{18}$$

where $\Pr_{o,j}^{(f)}$ is the outage probability in cell j within carrier f and is computed using (17), Φ_j the set of carriers allocated to cell j and $n_j^{(f)}$ the number of users in cell j associated to carrier f. The cumulative distribution function of mobile path losses towards the serving cell in (17) is statistically collected from path loss measurements. This outage estimation has been validated extensively by means of system-level simulations.

The feasibility test requires the number of carriers F_j allocated to each cell, sets Λ_f corresponding to all carriers, coupling matrix $\boldsymbol{C}$ and noise power vector $\boldsymbol{P}_N$. At the initialisation, the algorithm computes carrier's coupling matrices and noise power vectors using (10) and (11) for all carriers. Then, the spectral radius $\rho(\boldsymbol{C}^{(f)})$ of each carrier's coupling matrix is computed.

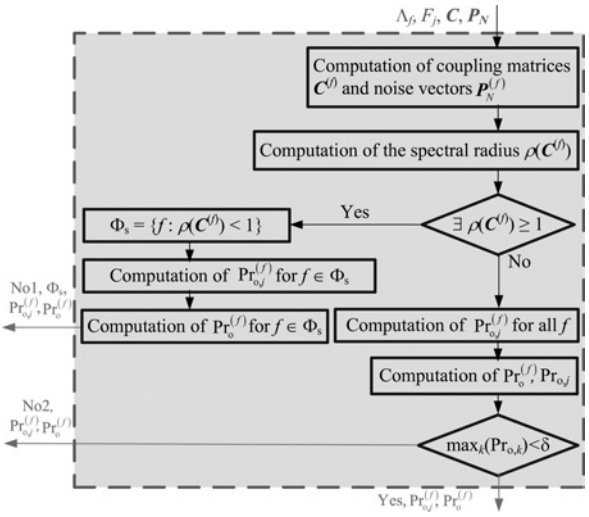

Figure 2 *Feasibility test diagram*

If one spectral radius is higher than unity, the system is not feasible according to the conclusions of [19], meaning that it is not possible to provide the required services to the users in the different cells. In this case, we take the set of carriers having a spectral radius lower than unity $\Phi_s = \{f: \rho(\boldsymbol{C}^{(f)}) < 1\}$ and compute, for each carrier f of set Φ_s, the outage probability $\Pr_{o,j}^{(f)}$ of cell j in carrier f using (17) and taking into account the interference vector $\boldsymbol{I}^{(f)}$ which is computed using (3) and by replacing $\boldsymbol{C}$ and $\boldsymbol{P}_N$ by $\boldsymbol{C}^{(f)}$ and $\mathbf{P}_N^{(f)}$

$$\mathbf{I}^{(f)} = (\Im_K - \boldsymbol{C}^{(f)})^{-1} \boldsymbol{P}_N^{(f)} \tag{19}$$

where $\Im_{|\Lambda_f|}$ is the $|\Lambda_f| \times |\Lambda_f|$ identity matrix.

By using the estimated outage probabilities, we compute the maximum outage probability in each carrier of set Φ_s

$$\Pr_o^{(f)} = \max_{j\in\Lambda_f}\left(\Pr_{o,j}^{(f)}\right) \tag{20}$$

In this case, the output of the feasibility test will be a set of parameters which are: set Φ_s, $\Pr_{o,j}^{(f)}$, $\Pr_o^{(f)}$ and the string 'No1', which indicates that the system is not feasible with reason number 1 (Table 2).

If all spectral radii are lower than unity, the outage probabilities $\Pr_{o,j}^{(f)}$ are computed for all carriers as in the first case using (17) and (19). Moreover, the total outage probability $\Pr_{o,j}$ of each cell j and the maximum outage probability $\Pr_o^{(f)}$ in each carrier are computed using (18) and (20), respectively.

Then, the maximum outage probability $\Pr_{o,\max} = \max_{j\in\Lambda}\left(\Pr_{o,j}\right)$ is compared with threshold δ. In this case, the output of the feasibility test will be a set of parameters which are: $\Pr_{o,j}^{(f)}$, $\Pr_o^{(f)}$ and the string 'No2' (which indicates that the system is not feasible because of reason number 2) if $\Pr_{o,\max} > \delta$ or the string 'Yes' otherwise (which

Table 2 Feasibility test outputs

Output	Reason	Parameters
Yes	the system is feasible: $\max_{f\in\Phi}(\rho(\boldsymbol{C}^{(f)})) < 1$ and $\Pr_{o,\max} < \delta$	Yes, $\Pr_{o,j}^{(f)}$ and $\Pr_o^{(f)}$
No1	the system is not feasible because $\exists f \in \Phi$, $\rho(\boldsymbol{C}^{(f)}) \geq 1$	No1, Φ_s, $\Pr_{o,j}^{(f)}$ and $\Pr_o^{(f)}$
No2	the system is not feasible: $\max_{f\in\Phi}(\rho(\boldsymbol{C}^{(f)})) < 1$ and $\Pr_{o,\max} \geq \delta$	No2, $\Pr_{o,j}^{(f)}$ and $\Pr_o^{(f)}$

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indicates that the system is feasible). The outputs of the feasibility tests are summarized in Table 2.

3.5 Carrier-to-cell allocation

Once the number of carriers per cell is obtained, the next step is to decide which specific carriers are selected for each cell. This carrier-to-cell allocation process can respond to different objectives depending on the specific operator strategy. For instance, an operator may need a large area where some carriers are not used in order to use these carriers in other RATs or to release them to a secondary market. Another objective could be simply to increase spectrum efficiency. In that respect, two different methodologies are presented to reflect these objectives.

3.5.1 Methodology 1: The objective of carrier-to-cell methodology 1 is to create large geographic zones where some carriers of the F_{av} carriers are unused and could be used by other RATs/operators or by secondary cognitive radio users. In order to increase areas where carriers could be released, we introduce the simple algorithm depicted in Fig. 3: the first carrier will be allocated to all cells, the second to all cells requesting at least two carriers the third to all cells requesting at least three carriers, and so on. The obtained sets are sent to the feasibility test together with the number of carriers allocated to each cell, the coupling matrix and the noise power vector. Depending on the result of the feasibility test, we have three different outputs

- If the output is 'No1', the system is not feasible because of spectral radius and the outage probability cannot be computed. Therefore the worst cell is chosen to be the cell satisfying

$$j = \arg\max_{k\in\Lambda} \sum_{l\in\Lambda} \frac{(C_{k,l} + C_{l,k})}{F_k} \tag{21}$$

If the output is 'No2', the system is not feasible because of high outage probability and the worst cell is chosen to be the cell with the highest outage probability

$$j = \arg\max_{k\in\Lambda} (\mathrm{Pr}_{o,k}) \tag{22}$$

- If the output is 'Yes', the system is feasible.

In the first two cases, the output of the carrier-to-cell allocation includes the string 'No' signalling that the system is not feasible in addition to the index of the worst cell j. In the third case, the output includes the global number of carriers F, the number F_j of carriers allocated to cell j and sets Λ_f.

3.5.2 Methodology 2: The carrier-to-cell allocation methodology 2 (see Fig. 4) is an extension of the algorithm in [20] where it was assumed that only one carrier could be assigned to a cell. This algorithm increases spectrum efficiency, whereas the large zones with free carriers will probably disappear. At the initialisation, all carriers are allocated to cells that require F carriers and a set A of

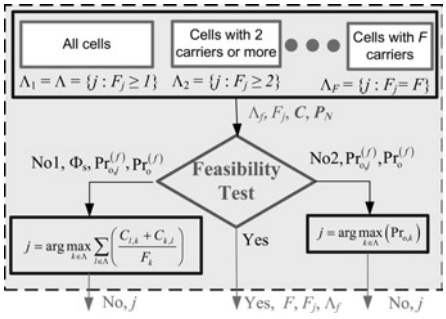

Figure 3 *Flow chart of the carrier-to-cell allocation in methodology 1*

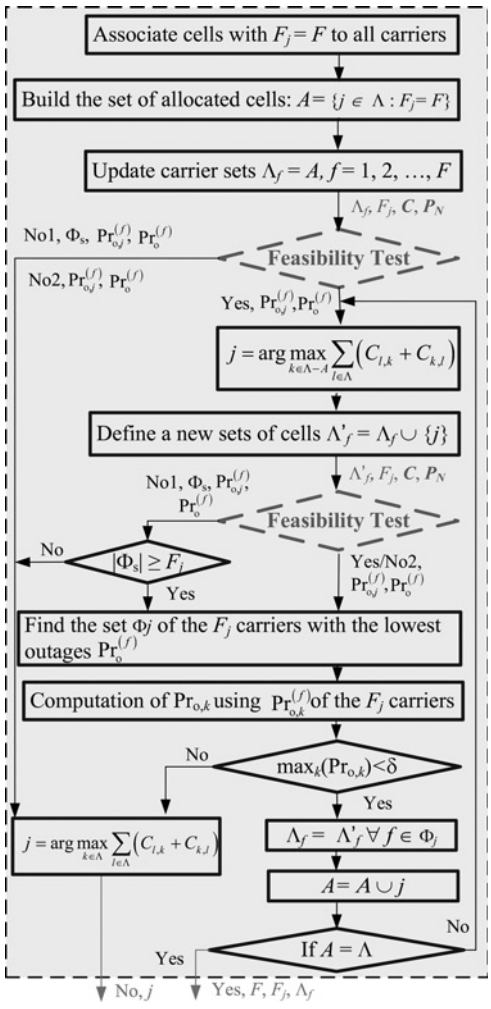

Figure 4 *Flow chart of the carrier-to-cell allocation in methodology 2*

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allocated cells is computed

$$\mathcal{A} = \{j \in \Lambda : F_j = F\} \tag{23}$$

Then, carrier sets Λ_f are updated

$$\Lambda_f = \mathcal{A} \quad \forall f \in \Phi \tag{24}$$

Thereafter, the feasibility test is performed using these sets. If the output string is 'No1' or 'No2', the system is not feasible and the worst cell j is chosen to be the cell satisfying

$$j = \arg \max_{k \in \Lambda} \sum_{l \in \Lambda} (C_{k,l} + C_{l,k}) \tag{25}$$

In this case, the output of the carrier-to-cell allocation block includes the string 'No' signalling that the system is not feasible, in addition to the index of the worst cell j. If the feasibility test is satisfied, a new cell from the non-allocated cells is chosen to be associated to carriers. The selected cell should have the highest inter-cell interaction between the non-allocated cells and therefore it satisfies

$$j = \arg \max_{k \in \Lambda - \mathcal{A}} \sum_{l \in \Lambda} (C_{k,l} + C_{l,k}) \tag{26}$$

As a result, new sets Λ'_f are associated temporary to the carriers

$$\Lambda'_f = \Lambda_f \cup \{j\} \tag{27}$$

Then, the feasibility test is performed again using the new sets in order to find the best carriers for cell j. If the output string of the feasibility test is 'No1', the methodology tests if the system is feasible in at least F_j carriers which are required by cell j

$$|\Phi_s| \geq F_j \tag{28}$$

If this condition is not satisfied, the system is not feasible and a worst cell j is chosen using (25). In this case also, the output includes the string 'No' signalling that the system is not feasible, in addition to the index of the worst cell j.

In case that condition (28) is satisfied or the output string of the feasibility test is either 'No2' or 'Yes', the best F_j carriers are chosen. These carriers should have the lowest outage probabilities $\Pr_o^{(f)}$ (i.e. the carriers where cell j has the lowest impact) and form set Φ_j. Then, the outage probability of all cells is computed using (18) and considering that only the F_j carriers are allocated to cell j. Moreover, the outage probabilities in the other carriers are the same as in the previous iteration. Cell's outage probabilities are then compared with δ. If the maximum outage probability is higher than δ, then the system is not feasible and a worst cell j is chosen using (25). In this case, the output includes the generic output 'No' signalling that the system is not feasible and the worst cell j. Otherwise, cell j is added to the set of allocated cells $\mathcal{A}$ and the sets Λ_f corresponding to carriers of set Φ_j are updated

$$\Lambda_f = \Lambda'_f \quad \forall f \in \Phi_j \tag{29}$$

If all cells are allocated, the output includes the global number of carriers F, the number F_j of carriers allocated to cell j and sets Λ_f. Otherwise, a new iteration is carried out.

4 Simulations and results

The simulation layout and simulation parameters are introduced in Fig. 5 and Table 3. We assume that the operator has three carriers at the beginning of simulations ($F_{\text{av}} = 3$). Although the proposed methodology has been developed from a generic perspective, being able to handle multiple services, a single service scenario is considered in the presented simulations for the sake of brevity and in order to illustrate the obtained performance. The results of the proposed ASM methodologies 1 and 2 are compared with the following two frequency allocation methodologies.

- The reference allocation is the simplest methodology and it consists of uniformly distributing the three carriers over cells whatever the cell loads are (i.e. always $F_j = F = F_{\text{av}}$).

- The uniform allocation assumes that all cells have the same number of carriers which is the maximum of F_j computed using a similar methodology as ASM methodology 1 but when QoS constraints are not satisfied, the number of carriers of all cells is increased by one, instead of increasing only the number of carriers in the worst cell. In this methodology, carriers could not be released locally even if the QoS levels were satisfied.

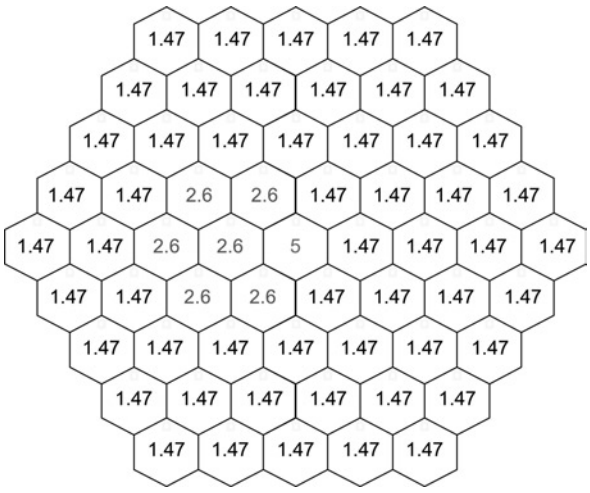

Figure 5 *Simulation layout*

Numbers inside cells are the percentage of users in each cell in respect to the total number of users in the system

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Table 3 Simulation parameters

BS pilot power, dBm	30
cell radius, km	1
path loss model, km	$128.1 + 37.6 \times \log_{10} d$
background noise power, dBm	−103
maximum allowed power, dBm	21
transmitted power range, dB	61
E_b/N_o target, dB	3
spreading factor Θ, dB	23
shadowing factor deviation, dB	7
shadowing factor cross-correlation	0.5
power control	Perfect power control
outage probability threshold δ	0.05

Fig. 6 shows the variation of the maximum outage probability as a function of the total number of mobiles in the system. The results show that the uniform allocation and the proposed ASM methodologies are able to adapt the number of allocated carriers to cells in order to maintain outage probabilities below threshold $\delta = 0.05$ and this is due to the accuracy of outage probability estimation methodology. It should be noted here that the purpose of the algorithm is not to minimise the outage probability but to guarantee that it is always under threshold δ, while reducing the number of allocated carriers. This justifies that no improvement in terms of outage is obtained with respect to the uniform allocation.

Spectrum efficiency υ is plotted in Fig. 7 as a function of the total number of mobiles where a circuit switched service with 12.2 Kbps useful data rate is considered. Moreover, Fig. 7 shows the global number of carriers used by the uniform distribution and the proposed ASM methodologies. The

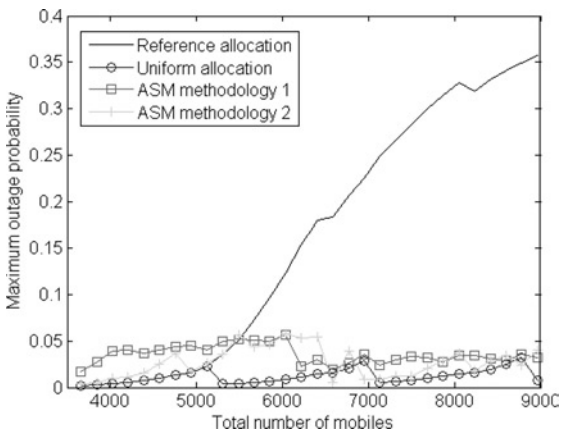

Figure 6 *Maximum outage probability over all cells*

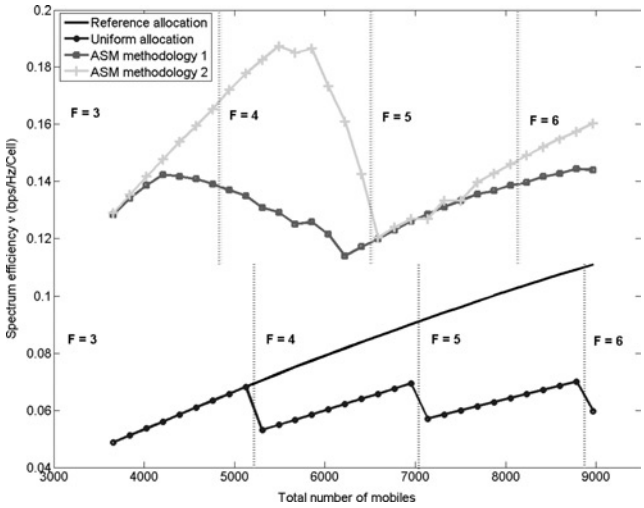

Figure 7 *Spectrum efficiency*

vertical dotted bars represent the switching point after which the global number of carriers F is increased by one. The colour of each vertical bar corresponds to that of the corresponding methodology, so that the upper bars correspond to ASM methodologies 1 and 2, whereas the lower bars correspond to the uniform allocation. For the reference allocation, the number of carriers is always 3. The proposed ASM methodologies maintain the highest spectrum efficiency because of the fact that they are able to find the minimum number of carriers needed by each cell while keeping the QoS of users at an acceptable level. Moreover, the ASM methodology 2 has better spectrum efficiency because of the fact that it finds the best carrier-to-cell allocation for given number of allocated carriers to each cell. The reference allocation has an increasing spectrum efficiency because of the fact that only three carriers are used always. However, the QoS constraints are not satisfied and thus the uniform distribution is more suitable in the sense that it can detect when the number of carriers should be increased. As we can see in Fig. 7, the proposed methodologies can increase the global number of

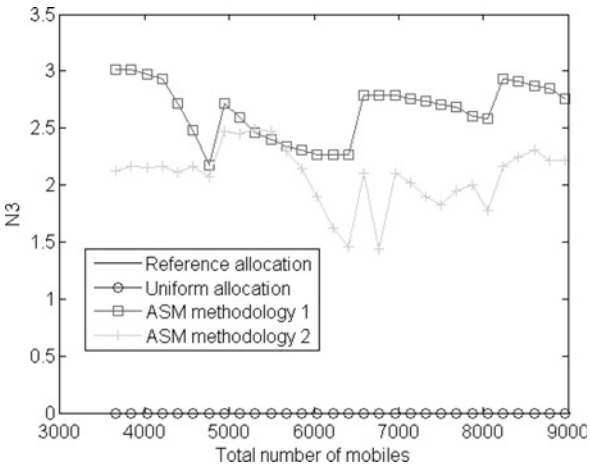

Figure 8 *Variation of N3 with the total number of users*

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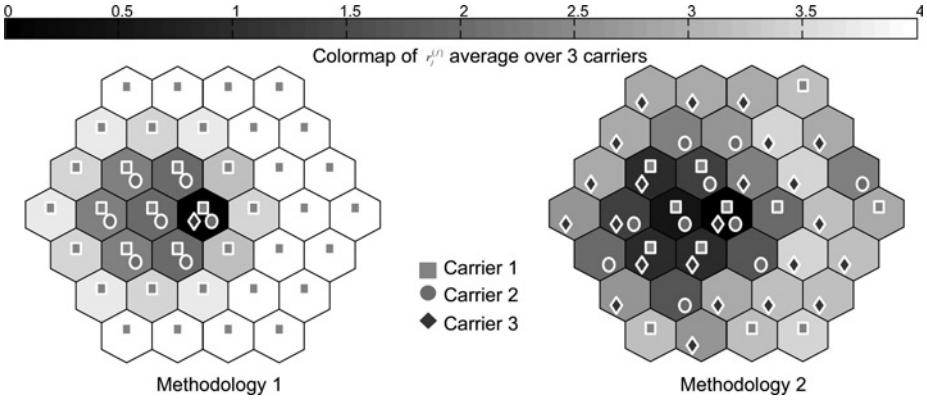

Figure 9 *Carrier distribution and the mapping of the average $r_j^{(f)}$ over three carriers when the proposed ASM methodologies are deployed in a system with 3660 mobiles*

carriers for lower loads than the uniform distribution. However, looking in more detail to the scenario, we have noticed that only the central cell with the highest load increases its number of carriers earlier in the proposed methodologies (these results are not shown here for the sake of simplicity). This is due to the high heterogeneity in the traffic distribution and the fact that the proposed methodologies allocate the carriers in a cell-by-cell scheme and not to the whole network. This is why the proposed methodologies increase system efficiency by more than 85% when compared with the uniform distribution.

However, the spectrum efficiency is not the only relevant parameter in scenarios where the operator wants to release a set of carriers that could be used by other RATs/operators/secondary market. In this case, it is beneficial if the carriers are released in a significantly large area (e.g. a set of neighbouring cells). Unfortunately, the spectrum efficiency cannot reflect this situation. For instance, a system with a non allocated carrier in n cells will have the same spectrum efficiency either if the cells are spread over the system or if they are concentrated in one zone, but the latter situation would be more suitable for the operator because of interference decrease if a secondary network is deployed in the centre of this zone. Therefore we propose a new metric to detect these situations and that can be used in addition to the spectrum efficiency. The new metric, called number of non-interfering neighbours (N3), is based on the following measurement for one cell and one carrier

$$r_j^{(f)} = \begin{cases} 0 & \text{if} \quad j \in \Lambda_f \\ |\Delta_j^{(f)}| & \text{otherwise} \end{cases} \tag{30}$$

where $\Delta_j^{(f)}$ is the set of adjacent cells to cell j that are not using carrier f. Therefore $r_j^{(f)}$ is the number of adjacent cells to cell j that are not associated to carrier f when cell j is not associated to carrier f. If $r_j^{(f)}$ is high enough (e.g. $r_j^{(f)} = 6$ in a hexagonal macro-cell scenario), carrier f could be used in cell j by another RAT/operator without being interfered/interfering neighbouring cells. Then, N3 is the average of $r_j^{(f)}$ over all cells and carriers

$$\text{N3} = \sum_{j=1}^{K} \sum_{f=1}^{F} \frac{r_j^{(f)}}{KF} \tag{31}$$

In Fig. 8, N3 is plotted as a function of the total number of mobiles. As we can see, the best methodology in terms of N3 is the ASM methodology 1 since it increases the number of neighbouring cells where a carrier could be released. Moreover, the reference and the uniform allocation always give a null value of N3 since all carriers are allocated to all cells. It should be noted that the N3 has an irregular shape in case of methodology 2 because it does not take this parameter into account in the optimisation process.

From the results of the two metrics, we can see that a methodology could have the highest spectrum efficiency without having the highest N3. However, good spectrum efficiency will lead for sure to good N3 and vice versa. Therefore these two metrics could be used simultaneously by an operator and higher weights could be given to one or the other depending on the objectives of the operator.

In Fig. 9, the carrier-to-cell allocation is plotted for one case of cell loads when the two ASM methodologies are used. The 24 border cells are not considered in this figure in order to eliminate border effect. We can see that carriers 2 and 3 are not allocated in large areas when methodology 1 is used while they are spread over the system when methodology 2 is used. This figure shows also the average of $r_j^{(f)}$ over the three carriers for both methodologies in each cell and we can see that in methodology 1, the value of this average is higher than that in methodology 2.

5 Conclusions

In this paper, we have introduced centralised ASM methodologies for the uplink of WCDMA networks. These methodologies aim at minimising the number of needed carriers in a cell-by-cell approach and satisfying

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mobile's QoS levels. This approach leads to the release of several carriers in large geographical areas where opportunistic access to the spectrum is allowed to cognitive radios.

The proposed approach is based on the utilisation of coupling matrix properties to reduce inter-cell interactions. Moreover, we have proposed two methodologies that reflect possible operator policies whose objective could be either to release carriers in large geographic areas or to increase spectrum efficiency. Thereafter, we have proposed a new metric that reflects the area size where cognitive radio users could access to the released spectrum without generating harmful interference.

Simulation results have shown that the new proposed metric is a necessary complement to the spectrum efficiency. Moreover, the proposed methodology has shown interesting results in terms of guaranteeing QoS levels reflected by outage probability and fulfilling operator policies. Our future work will focus on the utilisation of the released carriers by cognitive radios without polluting WCDMA users with harmful interference.

6 Acknowledgment

This work was performed in project E2R2/E3 which has received research funding from the Community's Sixth/Seven Framework program. This paper reflects only the authors' views and the Community is not liable for any use that may be made of the information contained therein. The contributions of colleagues from E2R2/E3 consortium are hereby acknowledged. The work is also partially funded by the Spanish Research Council under COSMOS (Ref. TEC2004-00518) grant.

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