A Novel Frequency Management Methodology for WCDMA using Statistical Coupling Matrices

J. Nasreddine, J. Pérez-Romero, O. Sallent, R. Agusti
TSC Department, Universitat Politècnica de Catalunya (UPC)
Campus Nord-D4, c. jordi girona, 1-3
08034 Barcelona, Spain
e-mail: [jnassred, jorperez, sallent, ramon]@tsc.upc.edu

Xavier Lagrange
RSM Department, GET/ENST de Bretgane
2 rue de la châtaigneraie, CS 17607, 35576
Cesson Sévigné Cedex, France
e-mail : xavier.lagrange@enst-bretagne.fr

Abstract— **Future wireless systems are expected to endure significant increase in cell loads as well as non-uniform distribution of the traffic over cells. Hence, interference profiles are subject to high increases that can highly affect interference limited systems. The allocation of several frequencies to each operator in 3G systems presents new dimensions to reduce interference patterns by the use of intelligent frequency management methodologies. However, the frequency management problem has not been sufficiently studied for WCDMA systems due to the fact that WCDMA has not yet been implemented in wide range with all possible services. Nevertheless, the arrival of multimedia services will emphasize the critical importance of a smart frequency allocation. Herein, we introduce a novel frequency management methodology based on statistical coupling matrices that reflect the interaction between cells for a given interference pattern. The proposed methodology is implemented as an integral task of the planning tool and has lead to better results than the frequency allocation in the classical hierarchical cell structure.**

Keywords- Frequency management methodology, coupling matrix, WCDMA

I. INTRODUCTION

A typical radio network rollout in early deployment phases of WCDMA systems is based on outdoor macro-cells with a progressive increase in the number of sites to provide the desired coverage area as well as sufficient network capacity. At this phase, one block of spectrum (i.e. one frequency carrier) could be enough if a frequency reuse factor of one is allowed. However, with increasing traffic demand together with the appearance of non-homogeneous traffic distributions and non-homogeneous mobility patterns, additional carriers may be required and the non-homogeneities are eventually treated by deploying micro-cells in high traffic areas, leading to Hierarchical Cell Structures (HCS) [1]-[3]. In that sense, it is usual to operate the different cell layers with different carrier frequencies, although depending on the specific interference levels, this condition may be broken. For instance, scenarios breaking the HCS in WCDMA systems are investigated in [4] and it has been shown that in some cases it is more suitable to share a frequency by both layers. Nevertheless, the spectrum management problem neither has to be limited to HCS nor it has to be presumed that it has a priori guide on a suitable solution, since it is strongly dependant on interference and traffic distribution along the deployed scenario. Therefore, spectrum management methodologies based on system characteristics can be of particular interest in next generation networks.

In the actual deployment of WCDMA systems, the number of used carriers by one cell is limited to one to reduce deployment complexity (i.e. each cell is served by one transceiver/receiver equipment). Therefore, we consider in this contribution that only one frequency could be allocated to each cell with the possibility to extend the proposed approach to the more general case where several carriers could be assigned to each cell in future studies. In this framework, the comprehensive spectrum management problem would be represented by a combinatorial optimization problem, whose objective is to find the frequency-to-mobile assignment that maximizes the number of satisfied users at each time unit. Unfortunately, this problem is very complex and could not be solved in real time (i.e. NP-hard problem). Therefore, a classical solution could be derived from existing call admission control (CAC) and radio resource management (RRM) techniques using a short-time scale methodology (e.g. when a user requests a call or needs a handoff, the frequency experiencing the lowest interference is chosen) in order to obtain acceptable results. Even though this methodology is able to offer a near-optimal solution in terms of minimizing the additional interference at a given time, the performance of the system over time could suffer from persistent equipment interactions. These interactions are very difficult to detect and are the result of random mobility, environment changes and non-optimal decisions of RRM and CAC algorithms. Therefore, if high spectrum efficiency is desired, then the total spectrum reallocation (i.e. all mobiles are associated to new frequencies as a result of solving an optimization problem) is needed again which is infeasible as we mentioned before. Herein, a promising feasible solution to the reallocation problem could be based on replacing frequency-to-mobile assignment by frequency-to-cell assignment so that the comprehensive problem is relaxed. This approach decreases drastically the complexity of the problem though long-term and acceptable performances are guaranteed. The frequency-to-cell was widely used in 2G systems and usually adopted with the traditional HCS in WCDMA systems.

A frequency-to-cell assignment methodology identifies cells with high interactions and avoids the allocation of the same frequency to these cells. Inter-cell interactions in WCDMA systems are correlated with different aspects of the radio interface such as inter-cell interference, intra-cell interference, cell loads, cell positions and mobile distributions in cells and in the whole system. This correlation leads to the possibility of developing different approaches that emphasize different aspects of the radio interface. In this paper, we propose a model based on the correlation between the total received powers of all base stations. The proposed model, called hereafter coupling matrix, focuses on the total received power though the other aspects are implicitly considered.

Once computed, the coupling matrix is used as an input for a frequency management methodology. The latter is implemented as a planning tool and aims to forbid cells with high interactions to share the same frequency. Furthermore, the proposed methodology can cope with the periodic variations that have quite fixed switching points between different traffic distribution periods. For instance, hotspots are mainly concentrated in working building (such as university, companies, etc). The planning tool could detect the fixed periods with different traffic distributions using expected cell loads. Then, it would generate the corresponding frequency allocation for each period together with the specific switching points. Then, the system will change from one frequency allocation to another using the switching points and the allocations generated by the planning tool.

The rest of this paper is organized as follows. In section II, we present the statistical coupling matrix. In section III, we introduce the frequency allocation algorithm that uses coupling matrices to reduce interference patterns. Section IV and V are devoted for simulation model and results. In section VI, we introduce some practical considerations. Finally, we conclude with relevant remarks and highlight open issues in section VII.

II. STATISTICAL COUPLING MATRIX

In this contribution, only uplink is considered since it is typically the worst case for frequency management methodologies based on inter-cell interference due to the high contribution of intra-cell interference (i.e. orthogonally factor is null). Nevertheless, a similar approach could be developed for downlink by using the total transmitted power by base stations instead of the total received power.

Let us consider a WCDMA system of K base stations and F frequencies. Our objective is to develop a matrix that reflects all inter-cell interactions. Interesting mathematical tools to assess the interaction of two different variables are second order statistics such as covariance and correlation factors. Using these tools, the network can isolate the interactions between two cells from the impact of other cells if a sufficient number of samples are available. In the following, we use the correlation coefficients of the total received powers as the entries of the coupling matrix. The c-th sample of the total received power by cell j is defined by

$$I_j = P_{R,j} + \chi_j + N_0 \tag{1}$$

where N_0 is the background noise power, $P_{R,j}$ is the total own cell power received by cell j and χ_j is the inter-cell interference experienced by cell j.

Using the correlation coefficients, we can define coupling matrix $\boldsymbol{C}$ by

$$C_{j,k} = cor\left(I_j, I_k\right) = \begin{cases} \dfrac{\sum_{c=1}^{\nu}\left(I_j^{(c)} - \overline{I_j}\right)\left(I_k^{(c)} - \overline{I_k}\right)}{\nu\sigma_j\sigma_k} & if \quad j \neq k \\ 0 & if \quad j = k \end{cases} \tag{2}$$

where ν is the number of samples, $\overline{I}_j$ is the mean value of vector $\boldsymbol{I_j} = \left(I_j^{(1)},\ I_j^{(2)},\ \cdots,\ I_j^{(\nu)}\right)$ and σ_j is the standard deviation of $\boldsymbol{I_j}$.

Matrix C takes into account only the variation of the total received power. However, cell load has also a significant impact on inter-cell interactions. In order to take into account this effect, we multiply each column by the corresponding cell load and a new coupling matrix A is defined by

$$\boldsymbol{A} = \boldsymbol{CB} \tag{3}$$

where $\boldsymbol{B}$ is a diagonal matrix whose entries are defined by

$$B_{jj} = \sum_{i_j=1}^{n_j} r_{i_j} \tag{4}$$

where r_{i_j} is the data rate of mobile i_j at physical layer in kb/s.

Notice that coupling matrix $\boldsymbol{A}$ is an asymmetric matrix due to the different cell loads. Therefore, the following symmetric matrix is defined

$$\boldsymbol{O} = \boldsymbol{C} + \boldsymbol{C^t} \tag{5}$$

where $\boldsymbol{A^t}$ is the transpose of $\boldsymbol{A}$. Each entry $O_{j,k}$ combines the impact of cell j on cell k and the impact of cell k on cell j.

In general, the correlation coefficient reflects the relative variation of one variable in function of the other. Obviously, if the mean interference in cell j increases the mean interference in cell k should increase when a mutual interaction between the two cells exists. In this case, the correlation coefficient between the two cells is positive and relatively high. In turn, when the mutual interaction between two cells is non-existent or very low, the correlation coefficient presents very low positive values converging to zero when the number of samples is very high. In practice, negative or positive low values could appear in this situation due to the finite number of samples. It should be emphasized here that if the number of these *illusive* values is relatively high, they may have a negative impact on results. Hence, a threshold value δ is considered: if the absolute value of the entry is smaller than the threshold, then this entry is rounded to zero.

III. FREQUENCY ALLOCATION ALGORITHM

The objective of the frequency allocation algorithm is to minimize the total outage probability in the system, which is defined as the ratio of unsatisfied users to the total number of users. A user is considered unsatisfied if its measured E_b/N_0 is lower than the target E_b/N_0. Moreover, the total outage probability in WCDMA systems is highly related to interference which in turn is related to the coupling matrix. Consequently, our objective is to minimize the interference profile using an offline heuristic algorithm that reduces inter-cell interactions.

Herein, we define X_f as the set of cells operating with frequency f. These sets are initially empty sets.

Using matrix $\boldsymbol{O}$, a heuristic algorithm that tends to avoid high interactions among cells is defined by the following steps:

1. **Cells are sorted using the sum of the corresponding rows in matrix *O*.**
2. **The *F* frequencies are allocated with one-to-one association to the first *F* cells with highest sum and sets X_f are updated.**
3. **For the next cell *i* of the remaining sorted cells, define the set of variables $\{\rho_f\}_{f=1..F}$ by:**

$$\rho_f = \sum_{k\in X_f \cup \{i\}} S_{i,k} \qquad \textbf{(6)}$$

4. **Thereafter, cell *i* is associated to frequency f_c such that:**

$$\rho_{f_c} = \min_{f\in\{1,\dots,F\}} \rho_f \qquad \textbf{(7)}$$

5. **Add cell *i* to set X_f. and repeat from step 3**

In each step, the algorithm reduces the impact of introducing a new cell on the existing cells and the impact of the latter on the new cell. At the beginning, frequencies are allocated to cells with the highest interference contribution because these cells have the highest impact on interference patterns. The remaining cells are then distributed so that the total inter-cell interaction is minimized. Using this method, we can avoid the allocation of the same frequency to cells with high interaction.

IV. SIMULATION MODEL

The performance of the proposed frequency management methodology has been evaluated by means of Monte Carlo simulations in a scenario with 37 macro-cells and a set of micro-cells. Each simulation consists of 10000 snapshots. In the simulation, each mobile is connected to the base station with the highest E_c/N_0 (signal energy per chip over Noise power spectral density) of the downlink pilot channel. Simulation parameters are summarized in table I.

In order to study the performance of the proposed scheme, the traditional HCS is considered as a reference for comparison purposes. In the HCS, macro-cells share the same frequency, while micro-cells (when they exist) share the second one.

The simulations have been carried out with four different representative case studies. In the first three cases, a first traffic layer is uniformly distributed and a second layer including dense hotspots is added.

Case study 1 corresponds to the first phase of WCDMA system deployment where hotspots start to appear, whereas no micro-cells are implemented. Consequently, only one frequency is used by the traditional HCS. The cell layout is the same as the layout shown in Fig. 1 without micro-cells. In case study 2, each hotspot is served by a micro-cell in the center of the hotspot (Fig. 1). In case study 3, the micro-cells are not at the center of the hotspots (Fig. 2). In case study 4, there are neither hotspots nor micro-cells, but each macro-cell has a different traffic density (Fig. 3). In each case study of the first three cases, three layouts, denoted as layout 1, 2 and 3 respectively, are considered with five, eight and ten hotspots with the corresponding micro-cells.

V. RESULTS

In this section, we present the results obtained using the different case studies and layouts. For illustration purposes, we show in Fig. 4 several values of matrix $\boldsymbol{O}$ from layout 2 of case study 2. We remind that the entries of matrix $\boldsymbol{O}$ are used by variables ρ_f. From this example we can see that the matrix efficiently reflects the interaction between cells. For instance, the interaction between micro-cells is low (40) because mobiles in these cells have very low pathloss toward their servers and very high pathlosses toward other base stations. However, the interaction between micro-cells and neighboring macro-cells is relatively high (97). Indeed, some mobiles that are geographically near to micro-cells are connected to a macro-cell due to the difference in pilot power. Therefore, these mobiles introduce high interferences into micro-cells. Moreover, the interaction between macro-cells is higher when the macro-cells are close. Thus, the proposed coupling matrix takes into account both cell loads and geographical positions.

In Fig. 1, Fig. 2 and Fig. 3, we show the resulting frequency configurations for case studies 2, 3 and 4 when the proposed methodology is used. Herein, cells with high loads (i.e. generally cells with high entries in the coupling matrix), tend in general to not share the same frequency with more than one neighboring cell. Moreover, the proposed method tends to allocate the same frequency to a set of neighboring cells when it is possible, which gives users the flexibility of smooth mobility without changing the frequency during each handover.

In Fig. 5, we show the total outage probability in the system when the HCS and the frequency management methodology are used for the first three case studies. As we can see, the proposed methodology reduces the outage probability by more than 50% in all cases. Moreover, the slope of the outage probability as a function of the number of hotspots (i.e. the different layouts) is smaller when the proposed methodology is used, especially when the micro-cells are not at the center of the hotspots (i.e. case study 3). This is due to the fact that the proposed methodology is hardly dependant on the number of hotspots in contrast to the HCS. In fact, when the number of hotspots increases, macro-cell loads increase due to their high pilot channel powers. Therefore, the inter-cell interactions between macro-cells increase. This type of interactions has high impact on the allocation used in the HCS since all macro-cells share the same frequency. In contrast, the flexibility of the proposed frequency management methodology allows the system to overcome this problem by changing the frequency allocation.

In the fourth case study, the outage probability decreases from 5.8% when HCS is used to 0.43% when the proposed scheme is used.

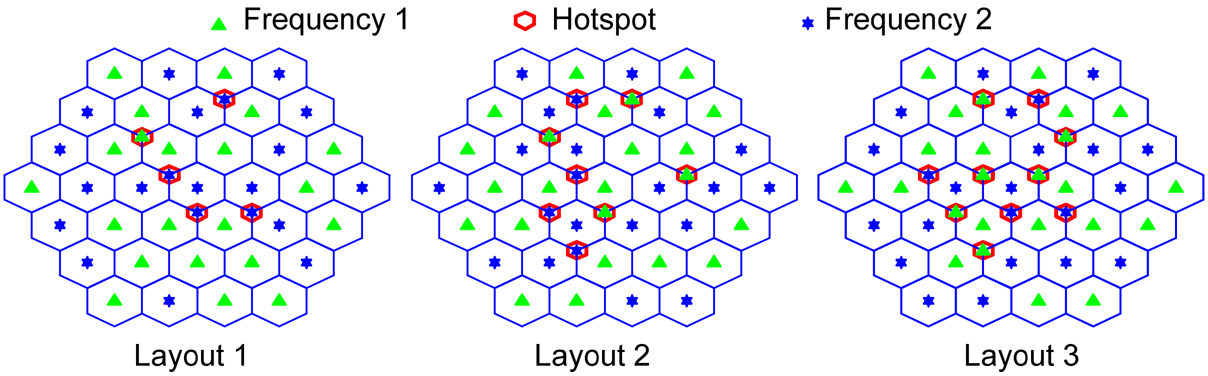

Figure 1. The three cell layouts and corresponding frequency allocation using the proposed coupling matrix for case study 2

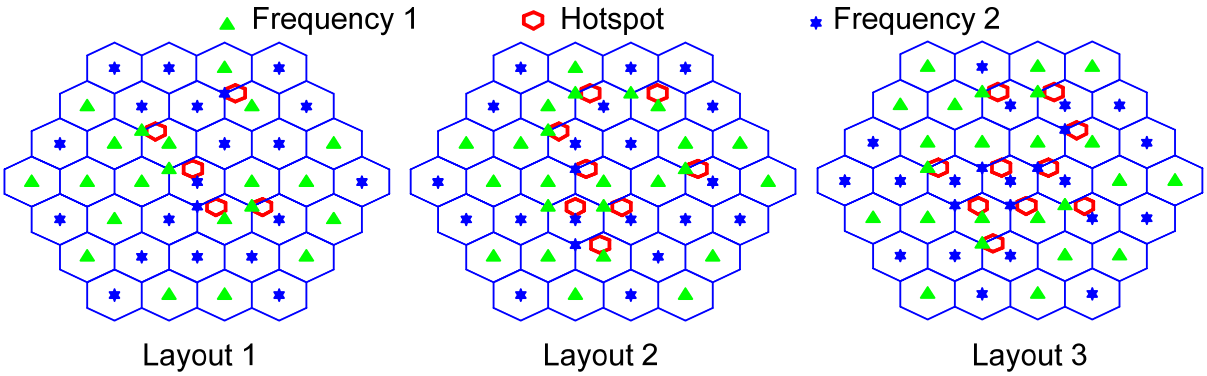

Figure 2. The three cell layouts and corresponding frequency allocation using the proposed coupling matrix for case study 3

In all cases, the traditional HCS appears to be unable to offer an acceptable assignment and an appropriate solution without adding more base stations. In contrast, the proposed methodology manifests as an elegant solution to solve this problem only by changing the frequency allocation. In brief, this solution will reduce the cost of operator infrastructure.

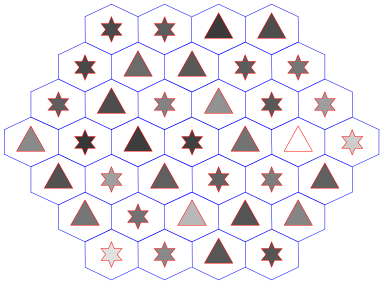

Figure 3. Cell layout in case study 4 and the frequency configuration using the proposed method (the gray level reflects the values of cell loads)

TABLE I. SIMULATION PARAMETERS

Macro-cell layer	
BS pilot power	30 dBm
Cell radius	0.6 km
Hotspot layer	
Micro-cell BS pilot power	12 dBm
Cell radius	0.2 Km
Common parameters	
Number of frequencies	2
Pathloss model	128.1+37.6 $\log_{10}d$ (Km)
Background noise	-103 dBm
UE maximum transmitted power	21 dBm
UE minimum transmitted power	-44 dBm
E_b/N_0 target	4 dB
Spreading factor	256
Shadowing factor deviation	10 dB
Shadowing factor cross-correlation	0.5
Power control	Perfect power control
Threshold of the coupling matrix (δ)	0.1

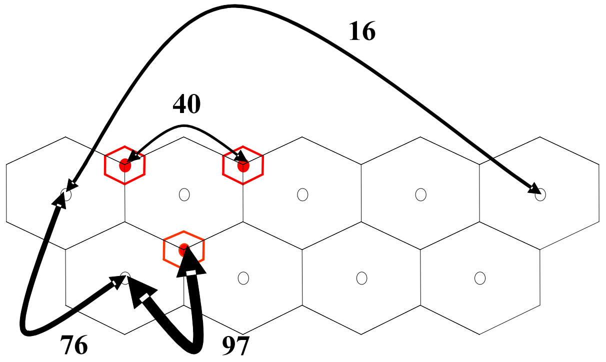

Figure 4. The entries of matrix $\boldsymbol{O}$ in case study 2 and layout 2

VI. PRACTICAL CONSIDERATIONS

The optimization algorithm complexity is a linear function of the number of cells. Therefore, its convergence is very fast (i.e. $O(K)$) and can be easily performed in operational systems even if a large set of cells are considered.

Besides, the coverage of an operator could be divided into bunches to facilitate the frequency management process. This scheme was used in second generation planning tools and could be extended to the third generation. In fact, each city can be considered an independent bunch thanks to the considerable distances between cells. In practice, a city could be covered in average using tenths or hundreds of macro-cells. Hence, the distribution of two or three frequencies over each city is relatively a simple task for planning tools.

We emphasize also that all the needed information for the computation of the proposed coupling matrices can be obtained using the measurements collected either by the base stations or the mobiles, as summarized in the following:

1. the bandwidth W and mobile data rates r_{i_j} are known by both base stations and mobiles
2. the total received power I_j used in both coupling matrices based on second order statistics and interference contribution is also measured by the base stations [5].

All information can be sent to the central control unit that performs the frequency management algorithm. Hence, the extension of a dynamic methodology is feasible.

VII. CONCLUSIONS AND FUTURE WORKS

In this paper, we have proposed a novel formulation of the interaction between cells for the uplink in WCDMA systems using second order statistics. This formulation is used to design an efficient frequency management methodology using a heuristic algorithm. Simulations results have shown that the obtained coupling matrix reflects efficiently inter-cell interactions. Furthermore, the proposed algorithm drastically decreases the outage probability when compared to the traditional allocation according to HCS.

The proposed scheme is an offline scheme at this stage. However, an online scheme that can cope with relatively fast variations in the system can be developed thanks to the interesting characteristics of the proposed matrix.

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REFERENCES

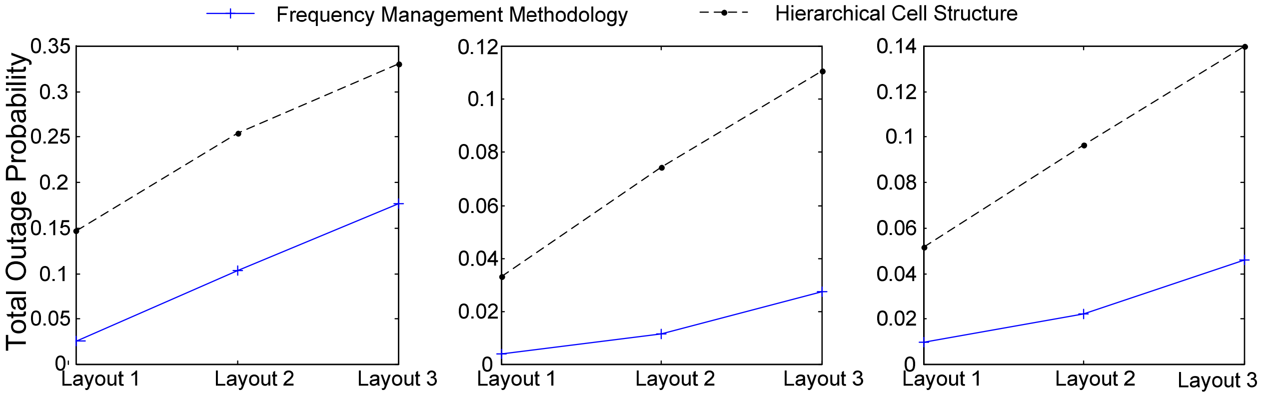
[1] UMTS Forum Report 5, "Minimum spectrum demand per public terrestrial UMTS operator in the initial phase", September 1998.

[2] UMTS Forum Report 6, "UMTS/IMT-2000 spectrum", December 1998

[3] "UE Procedures in Idle Mode and Procedures for Cell", 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, TS 25.304 V4.5.0, june 2002."TS 25.331 "Radio Resource Control (RRC)", 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, TS 25.331.

[4] T. Rautiainen, "Breaking the Hierarchical Cell Structure in WCDMA Networks", Proc. of the 55th IEEE VTC Spring conference, 2002.

[5] "Physical layer - Measurements (FDD)," Third Generation Partnership Project, Technical Specification Group Radio Access Network, TS25.215, July 2005



Case study 1 (mobile densities are 20 and 400 mobiles/km^2 respectively in the scenario and hotspots)

Case study 2 (mobile densities are 25 and 500 mobiles/km^2 respectively in the scenario and hotspots)

Case study 2 (mobile densities are 20 and 300 mobiles/km^2 respectively in the scenario and hotspots)

Figure 5. The total outage probability for the first three case studies and the three layouts