Dynamic Spectrum Management Methodology for WCDMA Systems Based on Inter-Cell Interaction Approach

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***Abstract*— Classical spectrum planning exercise is based on some expected spatial traffic distributions and corresponding load levels. Nevertheless, practical network deployments show that the dynamism in mobile scenarios and unpredictable changes in traffic distribution make traffic estimation severely frail. Hence, new approaches should be developed to detect the relevant changes in traffic distribution and find the adequate reaction. In this context, dynamic spectrum management methodologies would constitute a solid step forward towards innovative optimization mechanisms and cognitive networks. In this paper, we propose a novel dynamic spectrum management methodology based on inter-cell interaction approach characterized through coupling matrix properties. Simulation results for WCDMA systems have shown that the dynamic approach outperforms classical hierarchical cell structure planning.**

Key words: *Cognitive network, dynamic spectrum management, coupling matrix, WCDMA*

1. Introduction

NETWORK self-awareness and capability to optimize the use of precious radio resources in the unstable radio environment are momentous issues for future wireless networks. One key issue in these networks is that traffic distribution along time and space is inherently dynamic and subject to periodic changes on one hand and unexpected changes on the other hand.

Periodic traffic variations have a quite fixed switching point from one traffic distribution to another and can be predicted during the planning phase (e.g. hotspots are mainly concentrated in working buildings during the day). Thus, an off-line time-of-the-day spectrum management methodology (i.e. static methodology) is suitable for these scenarios. Namely, frequency-to-cell assignment in the planning phase manifests as a simple but efficient methodology that was widely used in 2G systems and adopted with the traditional Hierarchical Cell Structure (HCS) in WCDMA systems [1]-[4]. A more elaborated methodology was proposed in [5] for WCDMA systems, where an approach that deciphers inter-cell interactions using the so-called coupling matrix was developed. Then, the matrix was used as an input for the static spectrum management methodology.

It is fairly common that real traffic distributions are substantially different from those considered in a fixed planning phase due to sporadic and unexpected events. These events could occur at any time and could concern the average traffic level (e.g. an average traffic increase because tickets for a unique concert are starting to be sold in several shops at a given time and day) or the spatial traffic distribution while keeping the average traffic level (e.g. an entrance to an underground station is closed for maintenance for some days, so that people needs to get into the underground through a different entrance). Depending on the nature of these events, different types of variation can significantly alter inter-cell interactions leading to indispensable modification in spectrum allocation. Hence, the number of required frequencies as well as dynamic spectrum allocation methodologies should be considered in the framework of cognitive networks [6][7].

Despite that the static methodology in [5] is not designed to cope with sporadic changes, it engenders promising clues to develop a dynamic methodology. Indeed, coupling matrix approach manifests as a prominent indicator that can be used to develop Dynamic Spectrum Management (DSM) methodologies, allowing the system to monitor its environment, auto-detect relevant changes and find the best allocation as a step towards fully cognitive networks.

In the present contribution, we consider the uplink of a WCDMA system where a fixed number of frequencies are allocated to an operator. In the framework of cognitive networks, we extend the developed approach in [5] to design a comprehensive methodology for the DSM problem and we distinguish three main tasks:

- The computation of the coupling matrix that captures inter-cell interactions,
- The identification of the triggering events corresponding to important changes in traffic distribution,
- The specification of the suitable spectrum allocation in each period based on coupling matrix properties.

The rest of this paper is organized as follows. In section 2, we present the coupling matrix and its capability to detect important variations in the system. In section 3, we introduce a dynamic spectrum allocation methodology to cope with sporadic traffic variations. Section 4 is devoted for simulation model and results. Section 5 introduces some practical considerations. In section 6, we conclude with relevant remarks and highlight open issues.

2. Coupling Matrix

Let us consider a WCDMA system with K base stations and F frequencies. In this contribution, only uplink is considered. Nevertheless, a similar approach can be developed for downlink using the formulation initiated in [8]. The main idea of the coupling matrix is to reflect the interaction between the different base stations. Since inter-cell interactions are very complex (i.e. they depend on a plethora of radio characteristics such as inter-cell interference, intra-cell interference, cell loads, cell positions and mobile distributions in cells and in the whole system), several approaches can be formulated depending on the issues that have to be emphasized. In the framework of DSM methodologies that aims to reduce the interference pattern, the sensitivity of the total received power by one cell to the total received power by another cell manifests as an elegant indicator for inter-cell interaction.

In the following, I_j stands for the total power received by base station j and it is given by:

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

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

For a given scenario in a WCDMA system, the optimal performance, in the sense of satisfying all users and minimizing the power, is to find the power vector that satisfies the following equation for all users:

$$\left(\frac{E_b}{N_0}\right)_{i_j,\mathrm{th}} = \frac{P_{j,i_j}\Theta_{i_j}}{\left[P_{R,j} - P_{j,i_j}\right] + \chi_j + N_0} \tag{2}$$

Where i_j is the i-th mobile served by the j-th cell, $\left(E_b/N_0\right)_{i_j,\mathrm{th}}$ is the required E_b/N_0 by user i_j, P_{j,i_j} is the useful received power by base station j from mobile i_j and Θ_{i_j} is the spreading factor of mobile i_j including the modulation and code rate. It is shown in [5] that by using (2), we can write $P_{R,j}$ and χ_j as follows:

$$P_{R,j} = \sum_{i_j=1}^{n_j} P_{j,i_j} \tag{3}$$

$$\chi_j = \sum_{l\neq j}\sum_{i_l=1}^{n_l} \frac{L_{i_l,l}\times P_{l,i_l}}{L_{i_l,j}} \tag{4}$$

where $L_{i_k,j}$ is the pathloss of mobile i_k towards base station j and n_j is the number of users in cell j. Using these definitions and after mathematical manipulations, we can retrieve the following linear system of equations:

$$I_j = \frac{P_N + \sum\limits_{l\neq j} S_{l,j} I_l}{1 - S_{j,j}} \qquad \forall j = 1\cdots K \tag{5}$$

where:

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

The factor $S_{l,j}$ can be considered as an indicator of the influence of cell l on cell j that depends only on mobile pathlosses and services.

The vector of total received powers satisfying the system of equations (5) can be interpreted as the fixed point of a mapping $\mathcal{F}$:

$$\begin{array}{lll} \mathcal{F}: & \mathbb{R}_+^K & \to \mathbb{R}_+^K \\ & \boldsymbol{I} & \to \boldsymbol{CI} + \boldsymbol{P_N} \end{array}$$

where $\boldsymbol{P}_N = N_0\left(1/\left(1-S_{1,1}\right),\ 1/\left(1-S_{2,2}\right),\ \cdots,\ 1/\left(1-S_{K,K}\right)\right)^t$ is noise power vector and $\boldsymbol{I} = (I_1, I_2, \ldots, I_K)^{\mathrm{t}}$ is total received power vector.

The Jacobian $\boldsymbol{C}$ of mapping $\mathcal{F}$ is by definition the matrix of all partial derivatives of vector $\boldsymbol{I}$ and it is defined by

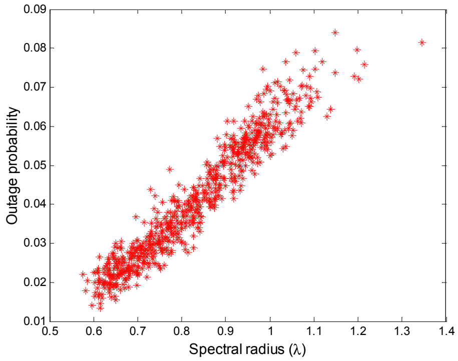

Figure 1: The outage probability as a function of the spectral radius for different mobile positions and cell loads

$$C_{j,l} = \frac{\partial I_j}{\partial I_l} = \begin{cases} 0 & \text{if } l = j \\ \dfrac{S_{l,j}}{1 - S_{j,j}} & \text{otherwise} \end{cases} \tag{7}$$

Each element of matrix $\boldsymbol{C}$, called hereafter coupling matrix, represents the impact of a cell total received power on another cell total received power.

Coupling matrix $\boldsymbol{C}$ has interesting properties that can be used as performance indicators. Namely, the spectral radius λ of the coupling matrix (i.e. the eigenvalue with the highest modulus) has a paramount impact on the interference pattern and thus on system performance (e.g. outage probability ϑ). This impact can be derived analytically in the same way as for transmitted power equations in [9] and [10]. However, it will not be developed herein since it is out of the scope of this contribution. Nevertheless, figure 1 shows the high correlation (0.8) between the spectral radius and the outage probability in a system of 37 macro-cells (1Km radius) and six hotspots served by six micro-cells (0.2 Km radius). All cells are sharing the same frequency and mobile density is ranging within intervals [19, 26] mobiles/Km^2 and [380, 520] mobiles/Km^2 in macro-cells and hotspots respectively.

Using linear interpolations, the relation between the two indicators could be approximated by

$$\vartheta = \xi\lambda + c \tag{8}$$

where ξ and c are scenario's constants (e.g. 0.12 and 0.54 respectively for the scenario depicted in figure 1). The values of ξ and c are not generic and depend on several parameters such as the ratio between inter-cell and intra-cell interference. A possible methodology to track the variations of ξ and c is to dynamically adjust theirs values by applying linear interpolation on the collected information in the framework of auto-learning and cognitive networks.

3. Dynamic Spectrum Management Methodology

The objective of the Dynamic Spectrum Management (DSM) methodology is to find the appropriate spectrum allocation that satisfies the maximum number of users at all periods of time. It aims at minimizing 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 required E_b/N_0.

The dynamic approach includes three main tasks performed by four blocks: the Coupling Matrix Block (CMB), the Triggering Event Block (TEB), the Spectrum Management Block (SMB) and a database. A general block diagram showing the main functional blocks is depicted in figure 2 and these blocks are introduced in the following. Moreover, two important time periods τ and T are defined to aggregate the collected information.

3.1. Coupling Matrix Block

The Coupling Matrix Block (CMB) is responsible for collecting the measurements needed to build the coupling matrix such as the required (E_b/N_0) and the averaged pathlosses of mobiles.

Periodically (i.e. each τ seconds), the CMB collects measurements from network nodes and updates the mean coupling matrix using the following relation:

$$\boldsymbol{C}_{\boldsymbol{m}}(n\tau)=\begin{cases}\boldsymbol{C}(n\tau)\dfrac{\tau}{T} & \text{if } n\tau\equiv 0 \mod(T)\\ \boldsymbol{C}_{\boldsymbol{m}}((n-1)\tau)+\boldsymbol{C}(n\tau)\dfrac{\tau}{T} & \text{Otherwise}\end{cases} \qquad (9)$$

where $\boldsymbol{C}(n\tau)$ is the measured coupling matrix considering all cells in all frequencies at time $n\tau$ and $\boldsymbol{C}_{\boldsymbol{m}}(n\tau)$ is the mean coupling matrix at time $n\tau$ and which is saved in the database. After each period T, the so called aggregate coupling matrix is computed:

$$\boldsymbol{C}_{\boldsymbol{a}}(nT)=\rho\boldsymbol{C}_{\boldsymbol{a}}((n-1)T)+(1-\rho)\boldsymbol{C}_{\boldsymbol{m}}(nT) \qquad (10)$$

where ρ is a filtering factor to smooth the variation of the coupling matrix. Once computed, the value of the aggregated matrix $\boldsymbol{C}_{\boldsymbol{a}}(nT)$ is saved in the database. At each sampling time nT, we derive F partial coupling matrices $\left(\boldsymbol{C}_{\boldsymbol{a}}^{(1)}(nT),\boldsymbol{C}_{\boldsymbol{a}}^{(2)}(nT),\cdots,\boldsymbol{C}_{\boldsymbol{a}}^{(F)}(nT)\right)$ from the total coupling matrix $\boldsymbol{C}_{\boldsymbol{a}}(nT)$. These matrices are the coupling matrices associated to the different frequencies; matrix $\boldsymbol{C}_{\boldsymbol{a}}^{(f)}(nT)$ includes only the entries corresponding to cells associated to frequency f. These partial coupling matrices are sent to the TEB.

The related database contains initially an aggregate coupling matrix issued from the planning tool [5].

3.2. Triggering Event Block

When relevant variations in the traffic distribution occur, prominent decrease in QoS levels (i.e. increase of outage probability) can affect some carriers. This means that some of the cells that share the affected carriers are experiencing high interactions and should no longer use the same carrier. Thus, the detection of this event is a very important key issue in the overall DSM methodology to guarantee the required QoS levels.

Following the analytical development in section 2, the triggering event will be related to the spectral radius of the coupling matrix due to the tight relation with the outage probability. Therefore, the Triggering Event Block (TEB) estimates the spectral radius of the F coupling matrices using numerical tools such as the power method [10].

At this stage, it is useful to introduce the following definition of the expected outage probability at time t:

$$\vartheta(t)=\frac{1}{N(t)}\sum_{f=1}^{F}N_f(t)\times\vartheta_f(t) \qquad (11)$$

where $N_f(t)$ is the average number of users associated to frequency f, $N(t)$ is the average number of mobiles in the system and $\vartheta_f(t)$ is the expected outage probability for frequency f. $N(t)$ and $N_f(t)$ are computed using the same procedure to compute the aggregated coupling matrix and they are saved in the database. Furthermore, $\vartheta_f(t)$ is computed using (8) and constant values of ξ and c.

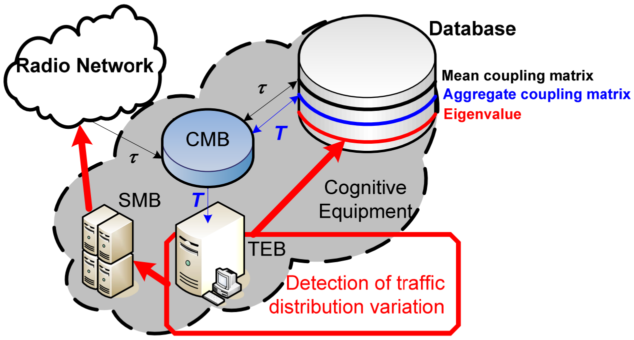

Figure 2: Basic block diagram for the DFM Methodology

A triggering event is detected when the expected outage probability is increased by more than threshold ϑ_{th}:

$$\vartheta(nT)-\vartheta((n-1)T)>\vartheta_{\text{th}} \qquad (12)$$

The variation of the outage probability is used instead of its current value because in some cases the outage probability cannot be decreased by the DSM methodology and this will lead to unnecessary complexity (by triggering DSM unnecessarily) if the current value is used. By using (8), (11) and (12), the triggering event is detected when the following criterion is fulfilled:

$$\sum_{f=1}^{F}\xi_f\left[N_f(nT)\lambda^{(f)}(nT)-N_f((n-1)T)\lambda^{(f)}((n-1)T)\right]>N(nT)\vartheta_{th} \qquad (13)$$

where $\lambda^{(f)}(nT)$ is the spectral radius of coupling matrix $\boldsymbol{C}_{\boldsymbol{a}}^{(f)}(nT)$.

Furthermore, a tradeoff should be taken between fast reactions to relevant changes on one hand, and system complexity and high traffic signaling on the other hand. Indeed, the system may endure high degradation in QoS levels if the triggering events are very distant. In contrast, if the triggering events are very close, the system will often change the spectrum allocation leading to unnecessary signaling load and eventually complicate the task of radio resource management techniques. This tradeoff can be considered in the DSM methodology by tuning ρ, T, τ, ϑ_{th} and ξ_f.

3.3. Spectrum Management Block

The Spectrum Management Block (SMB) is responsible for finding the appropriate spectrum allocation when a triggering event is detected. Since our objective is to minimize the outage probability and this indicator is highly correlated with the spectral radius of the coupling matrix, the objective of the SMB algorithm is to minimize the value of the maximum spectral radius over all carriers.

In order to introduce the algorithm, we define X_f as the set of cells operating with frequency f. The algorithm is performed at the planning phase as well as when a triggering event is detected and the resulting coupling matrices and spectral radius are saved in the database. The algorithm starts by re-initiating X_f to empty sets and it is defined by the following steps where the time index nT is omitted in the algorithm for simplicity:

1. All matrices $\boldsymbol{C}_{\boldsymbol{a}}^{(f)}$ are initiated to zero matrices: $\boldsymbol{C}_{\boldsymbol{a}}^{(f)}=0$.
2. A vector $\boldsymbol{V}=\{V_1, V_2, \ldots, V_k\}$ is computed. The value of V_j is computed using the sum of the corresponding rows and columns for each cell in matrix C:

$$V_j=\Sigma_{l\neq j}(C_{j,l}+C_{l,j})$$

3. Cells are sorted using the sum V_j in order to take into account the impact of each cell on other cells and the latter on each cell.
4. Cell j with the highest sum is associated to carrier 1 and set X_1 is updated. At this stage matrix $\boldsymbol{C}_{\boldsymbol{a}}^{(1)}$ will remain null.
5. Update each sum V_l of the remaining cells by eliminating the effect of the allocated cell j:
   $$V_l = V_l - C_{j,l} - C_{l,j}$$
6. Sort the remaining cells using the new vector $\boldsymbol{V}$ and choose cell j with the highest sum.
7. Estimate $\lambda^{(f)}$ for all carriers by considering that cell j is associated to all frequencies.
8. Choose frequency f with the lowest $\lambda^{(f)}$ and associate this frequency to cell j.
9. Add cell j to set X_f. and repeat from step 5

In each step, the algorithm reduces the impact of introducing a new cell on 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 entries, which should be avoided in the partial coupling matrices. The remaining cells are then distributed so that the total cell interaction is minimized. The obtained spectral radii are saved in the database.

4. Performance Evaluation

The performance of the proposed DSM methodology has been evaluated by means of dynamic simulations in a scenario with 37 macro-cells and six hotspots (served by six micro-cells) sharing two frequencies (figure 3). 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 1. In these simulations, sampling periods τ and T are respectively 1s and 10s while ϑ_{th}, ρ, ξ and c are fixed to 0.02, 0.9, 0.12 and 0.52 respectively.

In order to study the performance of the proposed scheme, the traditional HCS and the static methodology of [5] are considered as reference schemes for comparison purposes. In the HCS, macro-cells share the same frequency, while micro-cells share the second one. In the static methodology, the proposed algorithm of the SMB is only performed in the planning phase.

The simulations have been carried out with two representative case studies. Case study 1 corresponds to the first phase of WCDMA system deployment where the traffic density starts to increase drastically. The cell layout is the same as the layout shown in figure 3 without hotspot traffic movement. Initially, mobile density in macro-cells and hotspots are respectively 21.5 mobiles/Km^2 and 215 mobiles/Km^2. Mobile density increases by the same value at two points of time (after 33 and 66 minutes of simulated time) to reach respectively 24 mobiles/Km^2 and 835 mobiles/Km^2. In case study 2, the terminals of one hotspot are in mass-movement at 6 Km/h due to a non-periodic event such as the movement of people from a football stadium after a game (figure 3). Mobile density in macro-cells and hotspots are respectively 27 mobiles/Km^2 and 540 mobiles/Km^2.

Figure 4 and figure 5 show the evolution of the outage probability with time and the outage probability distribution function. Both spectrum management methodologies decrease the average outage probability by more than 50% when compared to HCS. Moreover, the dynamic approach retains only a slightly lower outage probability than the static methodology in case study 1. This is due to the fact that the increase in mobile density is pervasive and the spectrum re-allocation has a small effect on system performance. In case study 2 however, we can see the advantage of the dynamic approach that conserves a quasi-static high system performance when important variations occur and decrease the performance of the static methodology. This amelioration is provided by only detecting one triggering event when the users have moved for about 0.5 km.

5. Practical Considerations

The optimization algorithm complexity is a linear function of the number of cells. Besides, the coverage of an operator could be divided into bunches to facilitate the spectrum 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 cities. In practice, a city can 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 spectrum management methodologies. Moreover, all the needed information (E_b/N_0, long-term pathlosses, spreading factors) for the computation of the coupling matrices can be obtained using the measurements collected either by base stations or mobiles. Therefore, the DSM methodology can be easily implemented in operational systems.

6. Conclusions and Open Issues

In this paper, we proposed a dynamic spectrum allocation methodology based on inter-cell interaction detection. The proposed methodology outperforms the classical HCS planning and a recently proposed spectrum allocation methodology integrated in the planning tool.

This work is a step towards a complete dynamic spectrum management methodology where more than one frequency can be used by each cell. The next step is to elaborate the relation between the spectral radius and system performance indicators as well as the optimization of the DSM methodology by tuning the different parameters.

Table 1 Simulation Parameters

Macro-cell layer	
BS pilot power	30 dBm
Cell radius	1 km
Hotspot layer	
Micro-cell BS pilot power	20 dBm
Cell radius	0.2 Km
Common parameters	
Pathloss model	$128.1+37.6\times\log_{10}d$ (Km)
Background noise	-103 dBm
UE maximum transmitted power	21 dBm
UE minimum transmitted power	-44 dBm
E_b/N_0 target	3 dB
Spreading factor	23 dB
Shadowing factor deviation	10 dB
Shadowing factor cross-correlation	0.5
Power control	Perfect power control

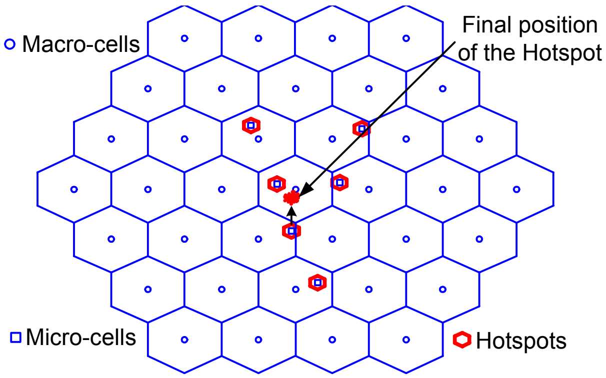

Figure 3: Cell layout and the final position of the hotspot for case study1

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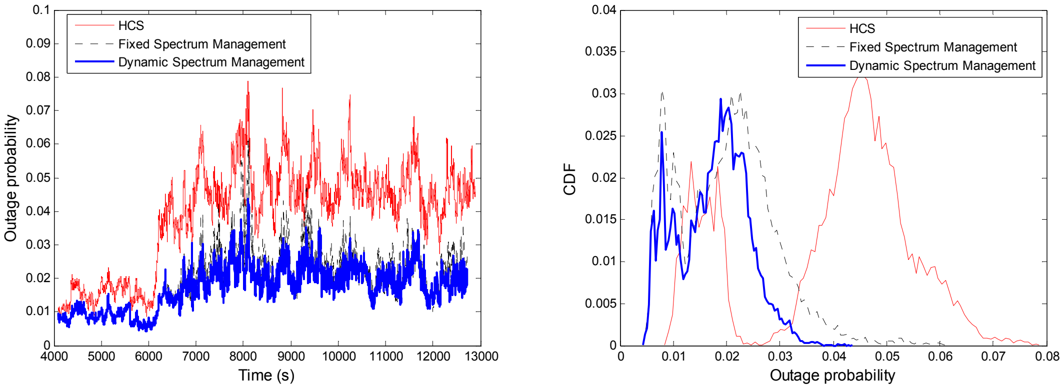

Figure 4: Performance of spectrum management methodologies for case study 1

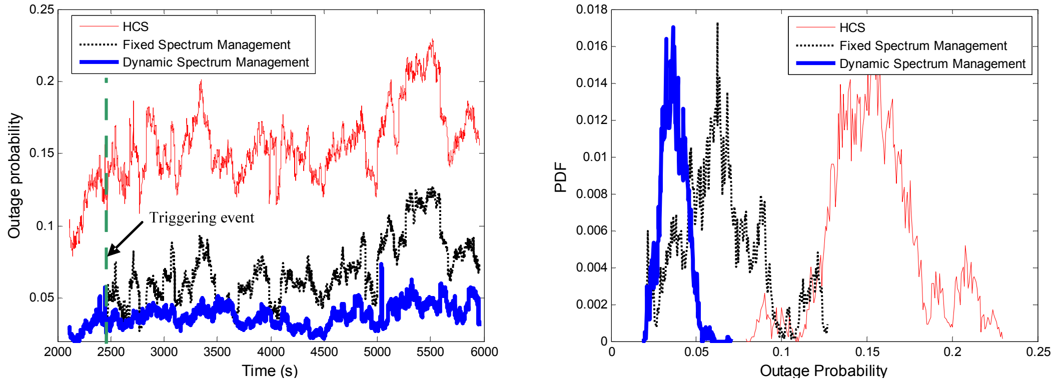

Figure 5: Performance spectrum management methodologies for case study 2