Spectrum Management Methodology for WCDMA Systems Encompassing Uplink and Downlink

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Abstract— **In this paper a new spectrum management methodology for WCDMA systems is proposed based on the concept of coupling matrix, which is able to capture inter-cell interactions. The proposed methodology takes into account the fact that uplink and downlink frequency carriers are jointly allocated and optimizes simultaneously the two link directions. Simulation results for symmetric and asymmetric services show the efficiency of the methodology in increasing capacity and reducing transmitted power.**

Keywords- Coupling matrix; Spectrum Management; WCDMA

I. Introduction

The tremendous increase in mobile user density and the pervasive non-homogeneity in both spatial and temporal traffic distribution in cellular systems (e.g. urban hotspots and rural environment, daytime and nighttime traffic distributions, etc.) require an evolution in the spectrum allocation vision for WCDMA systems. Traffic increase, together with non-homogeneity, leads to the presence of islands of saturated cells although the overall system may not be congested from a global point of view. This is due to the fact that some cells have high interactions leading to high inter-cell interference in addition to the difference in cell loads. In the presence of several frequencies (i.e. typically two or three), which is the case of currently deployed WCDMA systems, frequency carriers could be distributed in smart way in order to prevent such cells of sharing the same frequency.

Spatial non-homogeneity is currently faced 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 (i.e. macro-cell and micro-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 were 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 an 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 this context, we propose a heuristic spectrum management algorithm based on the concept of coupling matrix proposed in [5][6] for uplink and which is able to capture the interaction among the different cells from both macroscopic and microscopic points of view. In addition to the formulation of the coupling matrix for downlink, we propose in this paper a spectrum management methodology to distribute the available WCDMA frequency carriers among cells in a smart way. This paper assumes that the amount of traffic per cell is such that only one WCDMA carrier per cell is required, although the proposed methodology could be extended to the general case in which more than one carrier per cell is required.

The paper is organized as follows. In Section II, we introduce the coupling matrix for both uplink and downlink. In Section III, we present the spectrum management methodology. In Section IV, we describe the simulation model and provide some illustrative results in different scenarios. Finally, we conclude with relevant remarks and future work.

II. Coupling Matrix

Let us consider a WCDMA system with K base stations and F frequencies. The set of all base stations is called $\Lambda = \{j: j \in [1, K]\}$ and the set of all frequencies is called $\Phi = \{f: f \in [1, F]\}$. The number of users connected to base station j is n_j. In the following, two coupling matrices are developed for downlink and uplink respectively.

A. Downlink

In the downlink, the E_b/N_0 requirement for the i-th user of the j-th cell, denoted as user i_j, can be expressed as:

$$\left(\frac{E_b}{N_o}\right)_{i_j} = \frac{\frac{P_{T,i_j}}{L_{i_j,j}} \times \Theta_{i_j}}{N_{0,D} + \chi_{i_j} + \alpha_D \times \left[\frac{P_{T,j} - P_{T,i_j}}{L_{i_j,j}}\right]} \qquad (1)$$

where P_{T,i_j} is the power devoted to the user i_j, χ_{i_j} represents the inter-cell interference experienced by this user, Θ_{i_j} is the spreading factor including the modulation and code rate, $L_{i_j,j}$ is the pathloss between mobile i_j and base station j, α_D is the orthogonality factor in downlink (α_D = 0 for perfect orthogonality and 1 for non-orthogonality), $N_{0,D}$ is the downlink background noise power, and $P_{T,j}$ is the total transmitted power by base station j, which is given by

$$P_{T,j} = P_{p,j} + \sum_{i_j=1}^{n_j} P_{T,i_j} \tag{2}$$

where $P_{p,j}$ is the power devoted to common control channels in cell j.

It was shown in [7] that by using (1) and (2), we get

$$P_{T,j} = \frac{P_{p,j} + N_{0,D} D_j + \sum_{l\in\Lambda-\{j\}} P_{T,l} S_{j,l}}{1-\alpha_D S_{j,j}} \tag{3}$$

where

$$S_{j,l} = \sum_{i_j=1}^{n_j} \frac{L_{i_j,j}}{L_{i_j,l}} \frac{1}{\dfrac{\Theta_{i_j}}{\left(\dfrac{E_b}{N_o}\right)_{i_j}} + \alpha_D} \tag{4}$$

$$D_j = \sum_{i_j=1}^{n_j} \frac{L_{i_j,j}}{\dfrac{W/R_{i_j}}{\left(\dfrac{E_b}{N_o}\right)_{i_j}} + \alpha_D} \tag{5}$$

The cell coupling existing in a WCDMA cellular system is explicitly reflected in the above equation, where the resulting transmitted power level by a given base station depends on all other base stations' respective transmitted power levels.

In matrix form, the system of equations (3) is rewritten as

$$\boldsymbol{P_T} = \boldsymbol{C^D} \boldsymbol{P_T} + \boldsymbol{P_N^D} \tag{6}$$

where $\boldsymbol{P_T} = (P_{T,1}, P_{T,2}, \ldots, P_{T,K})^{\mathrm{T}}$ is the total transmitted power vector, the j-th element of $\boldsymbol{P_N^D}$ is defined by $P_{N,j}^{\boldsymbol{D}} = \left(P_{p,j} + N_{0,D} D_j\right) / \left(1-\alpha_D S_{j,j}\right)$ and the coupling matrix $\boldsymbol{C^D}$ is a $K\times K$ square matrix defined by

$$C_{j,l}^D = \begin{cases} 0 & \text{if } l = j \\ \dfrac{S_{j,l}}{1-\alpha_D S_{j,j}} & \text{otherwise} \end{cases} \tag{7}$$

From (3), we can infer that each element of coupling matrix $\boldsymbol{C^D}$ represents the impact of the total transmitted power by one base station on the transmitted power by another base station.

B. Uplink

In the following, I_j stands for the total power received by base station j and it is given by [7]:

$$I_j = \chi_j + P_{R,j} + N_{0,U} \tag{8}$$

where χ_j and $P_{R,j}$ are the inter-cell interference and the total own-cell received by cell j, and $N_{0,U}$ is the uplink background noise power.

In uplink, the E_b/N_0 requirement for the i-th user of the j-th cell can be expressed as

$$\left(\frac{E_b}{N_0}\right)_{i_j} = \frac{P_{j,i_j}\Theta_{i_j}}{\left[P_{R,j} - P_{j,i_j}\right] + \chi_j + N_{0,U}} \tag{9}$$

where P_{j,i_j} is the received power by base station j from user i_j.

It was shown in [5] that, by using (9), we can write

$$I_j = \frac{N_{0,U} + \sum_{l\in\Lambda-\{j\}} S_{l,j} I_l}{1-S_{j,j}} \quad \forall j \in \Lambda \tag{10}$$

It is worth mentioning that the coupling between the j-th cell and the l-th cell in the downlink is given by the term $S_{j,l}$ in (3), which depends on how the users are distributed within the j-th cell in relation to the l-th cell. On the contrary, the coupling in the uplink direction is given by the term $S_{l,j}$ in (10) which depends on how the users are distributed in the l-th cell with respect to the j-th cell.

In matrix form, the system of equations (10) can be rewritten as

$$\boldsymbol{I} = \boldsymbol{C^U} \boldsymbol{I} + \boldsymbol{P_N^U} \tag{11}$$

where $\boldsymbol{I} = (I_1, I_2, \ldots, I_K)^{\mathrm{T}}$ is total received power vector, the j-th element of $\boldsymbol{P_N^U}$ is defined by $P_{N,j}^{\boldsymbol{U}} = N_{0,U} / \left(1-S_{j,j}\right)$ and the coupling matrix $\boldsymbol{C^U}$ is a $K\times K$ square matrix defined by

$$C_{j,l}^U = \begin{cases} 0 & \text{if } l = j \\ \dfrac{S_{l,j}}{1-S_{j,j}} & \text{otherwise} \end{cases} \tag{12}$$

From (10), we can infer that each element of coupling matrix $\boldsymbol{C^U}$ represents the impact of the total received power by one base station on the total received power by another base station.

C. Generic Form

Equations (3) and (10) can be written in the following generic matrix form:

$$\boldsymbol{V} = \boldsymbol{C^L} \boldsymbol{V} + \boldsymbol{P_N^L} \tag{13}$$

where $\boldsymbol{V}$ is a Kx1 vector that replaces $\boldsymbol{I}$ in uplink and $\boldsymbol{P_T}$ in downlink and L is the link direction.

III. Spectrum Management Methodology

It can be shown that, using the same reasoning as in [8], the coupling matrices are non-negative irreducible matrices. When representing a system by a non-negative irreducible matrix, spectral radius (i.e. the eigenvalue with the largest modulus) can be seen as a smart indicator that is able to capture overall system behavior. Indeed, a pervasive increase in matrix elements (or an increase of any element) leads necessarily to an increase in the spectral radius of a non-negative irreducible matrix [9]. Furthermore, it was shown in [10] that the spectral radius of non-negative irreducible matrices could be used as a congestion measure. Therefore, in this paper we use the spectral radius of the coupling matrix as a key element of the proposed spectrum management algorithm.

A. Spectrum Management Algorithm

We assume the usual case in currently deployed WCDMA networks in which the operator has F frequency carriers to be distributed among the different base stations. The traffic level is such that only one carrier is required per base station, so the operator can take advantage of the availability of the F frequencies by means of a smart frequency-to-cell allocation in order to improve the interference pattern with respect to a classical frequency reuse-based approach.

In this paper, we assume that the spectrum management algorithm is implemented in the initial planning phase. However, it would be easy to extend the proposed approach to a dynamic methodology that uses coupling matrix properties to detect relevant changes and optimize frequency allocation as in the proposed approach for uplink in [11].

Using expected traffic levels, the operator can estimate the coupling matrices $\boldsymbol{C}^U$ and $\boldsymbol{C}^D$ from the reported values of pathlosses and E_b/N_0 for both uplink and downlink in a given coverage area. At each iteration of the algorithm, we derive $2F$ partial coupling matrices $\left(\boldsymbol{C}_1^D,\boldsymbol{C}_2^D,\cdots,\boldsymbol{C}_F^D,\boldsymbol{C}_1^U,\boldsymbol{C}_2^U,\cdots,\boldsymbol{C}_F^U\right)$ from the total coupling matrices $\boldsymbol{C}^D$ and $\boldsymbol{C}^U$. These matrices are the coupling matrices associated to the different frequencies, that is, matrix $\boldsymbol{C}_f^L$ includes only the entries corresponding to cells associated to frequency f in link direction L. In order to introduce the algorithm, we define Λ_f as the set of cells operating with frequency f and λ_f^L as the spectral radius of matrix $\boldsymbol{C}_f^L$.

The algorithm is shown in Figure 1 and it starts by initiating Λ_f to empty sets. Basically, the idea of the algorithm is to allocate each cell to the frequency in which the mutual interaction of this cell with the cells already allocated to this frequency is minimal.

B. Practical Considerations

From a practical point of view, the operator can identify different periods of time with different traffic distributions and associate to each period a different frequency allocation, based on the proposed methodology, so that the network configuration can be changed to adapt to the traffic variations. These periods are rather medium and long-term periods (i.e., at least several hours) and the elements of the matrix are estimated from the expected averaged values of $S_{l,j}$. In this context, the fast fluctuation (due to mobility, fast fading, etc.) is averaged and does not have important impact on the accuracy of the matrix. 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. Furthermore, the spectral radius can be computed using the power method [12].

The complexity of the spectrum management algorithm is a linear function of the number of cells. Besides, the coverage of an operator could be divided into bunches, so that the algorithm can be applied separately to each bunch, in order to facilitate the spectrum management process. Therefore, the coupling matrix approach could be easily implemented in operational systems.

1. All matrices $\boldsymbol{C}_f^L$ are initiated to zero matrices: $\boldsymbol{C}_f^L = 0$.
2. A vector $T = \{T_1, T_2, ..., T_K\}$ is computed. The value of T_j is computed using the sum of the corresponding rows and columns for each cell in matrices C^U and C^D:
$$T_j = \sum_{l\in\Lambda-\{j\}}\left(C^D_{j,l}+C^D_{l,j}+C^U_{j,l}+C^U_{l,j}\right)$$
Each element T_j combines the impact of cell j on other cell and the impact of other cells on cell j in both uplink and downlink
3. Cells are sorted using the sum T_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 Λ_1 is updated. At this stage $\boldsymbol{C}_1^L$ will remain null.
5. Update each sum T_l of the remaining cells by eliminating the effect of the allocated cell j:
$$T_l = T_l - \left(C^D_{j,l}+C^D_{l,j}+C^U_{j,l}+C^U_{l,j}\right)$$
6. Sort the remaining cells using the new vector T and choose cell j with the highest sum.
7. Estimate $\Omega_f = \max_{L=\{U,D\}} \lambda_f^L$ by considering that cell j is associated to all frequencies. Ω_f capture the behavior of the worst link and should be minimized.
8. Choose frequency f with the lowest Ω_f and associate this frequency to cell j.
9. Add cell j to set Λ_f. and repeat from step 5

Figure 1. Spectrum Management Algorithm

IV. SIMULATION AND RESULTS

The performance of the proposed methodology is compared to the performance of the spectrum allocation in the classical HCS approach in a scenario with F=2 frequencies using snapshot simulations. In the HCS, one frequency is assigned to macro-cells and the second one is assigned to micro-cells. The considered scenario consists of three macro-cell rings and seven hotspots with seven micro-cells in the center of the hotspots (Figure 2). Simulation parameters are introduced in Table I [13]. Three scenarios are considered. The first scenario considers an asymmetric traffic in which downlink spreading factor (SF) including the modulation and code rate is 20 dB while uplink SF is 26 dB, to account for the higher bit rate needed in downlink. On the contrary, the second scenario considers a symmetric traffic with the same SF=23 dB in uplink and downlink. Finally, the third scenario considers the symmetric traffic in macro-cells and the asymmetric traffic in hotspots.

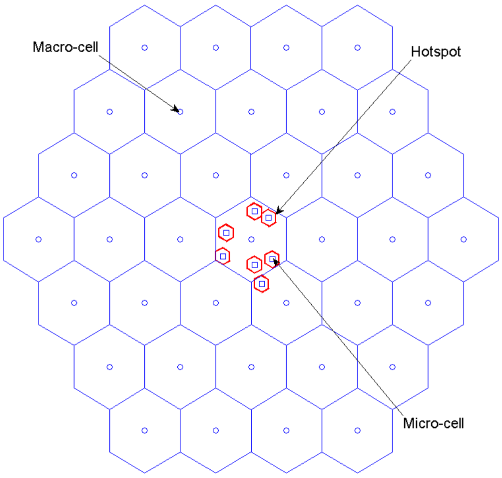

Figure 2. Layout of the macro-cells, micro-cells and hotspots

TABLE I SIMULATION PARAMETERS

Macro-cell layer	
BS pilot power	30 dBm
Cell radius	1 km
Orthogonality factor	0.4
BS maximum transmitted power	43 dBm
Micro-cell layer	
Micro-cell BS pilot power	20 dBm
Cell radius	0.2 Km
Orthogonality factor	0.06
BS maximum transmitted power	33 dBm
Common parameters	
Downlink BS power range	25 dB
Pathloss model	$128.1+37.6\times\log_{10}d$ (Km)
Background noise	-98 dBm
UE max. power for macro-cell (Downlink)	30 dBm (20 for micro)
UE max. power (Uplink)	21 dBm
Transmitted power range	25 dB
Downlink E_b/N_0 target	6 dB
Uplink E_b/N_0 target	3 dB
Shadowing factor deviation	7 dB
Shadowing factor cross-correlation	0.5
Macro-cell density (1^{st} sc.)	11 - 16 mobiles/cell
Micro-cell density (1^{st} sc.)	8.8:12.8 mobiles/cell (steps of 0.8 mobiles/cell)
Macro-cell density (2^{nd} sc.)	30 - 35 mobiles/cell
Micro-cell density (2^{nd} sc.)	24-28 mobiles/cell (steps of 0.8 mobiles/cell)
Power control	Perfect power control

In each snapshot a number of mobiles are randomly distributed in the scenario according to the spatial traffic pattern. All results are averaged over 1000 snapshots. In Figure 3, we show the total downlink outage probability of the asymmetric scenario as a function of average mobile density. The total outage probability is defined as the rate between the unsatisfied users (i.e. those users measuring an E_b/N_0 below the target) and the total number of users in the system. Average mobile density is defined by the ratio between the total number of users in the system and the total surface. Figure 3 shows that the proposed Spectrum Management Methodology (SMM) outperforms the HCS especially for high mobile density. Furthermore, the capacity (i.e. user density when the outage probability is 0.02) is increased by 20% when the SMM is used (i.e. from 10.7 to 12.9 mobiles/Km^2). We highlight here that for these densities and asymmetric traffic, uplink outage probability is very low (i.e. quasi-null) and thus the capacity of the system is limited by the downlink. In Figure 3 we also show the maximum outage probability among all cells as a new metric to detect islands of congested cells. Also from the point of view of this metric, the SMM outperforms the spectrum allocation in the HCS and gives approximately the same capacity gain as in the case when the total outage in the scenario is considered. In Figure 4, we show the average transmitted power over all base stations as a function of the average mobile density. As we can see, the SMM decreases significantly the transmitted power in the system thanks to the avoidance of high inter-cell interference.

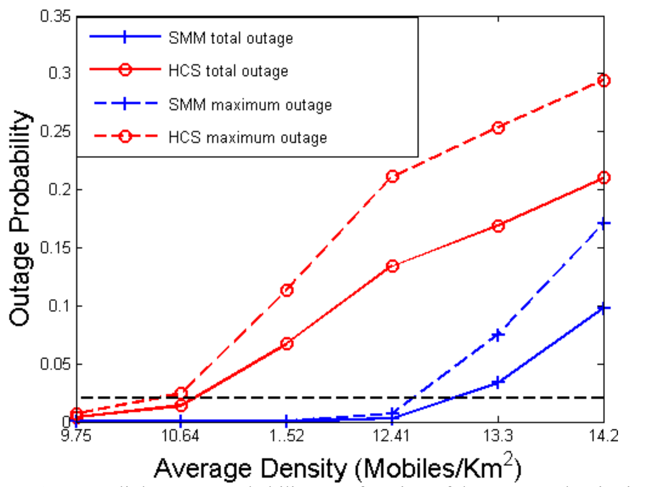

Figure 3. Downlink outage probability as a function of the average density in the asymmetric scenario

In Figure 5, the total outage probability in the symmetric scenario is plotted. When using the HCS, it can be observed that the uplink performance is better than the downlink one for low loads because the E_b/N_0 in downlink is higher than in uplink and the downlink orthogonality does not affect the inter-cell interference, which is similar in both uplink and downlink. On the contrary, when the SMM is used, the uplink is the limiting transmission direction. This is due to the fact that the SMM highly reduces the inter-cell interference and therefore the system is limited by intra-cell interference, which is higher in uplink than in downlink thanks to the orthogonality existing in the latter. Finally, we highlight the fact that the proposed method increases the capacity by more than 21% (i.e. from 25.7 to 31 mobiles/Km^2). Furthermore, the outage probability is significantly reduced when the SMM is used instead of the HCS in both uplink and downlink. Moreover, other simulation results not shown here for the sake of brevity reveal that also the average total transmitted power is reduced when the SMM is used instead of the HCS.

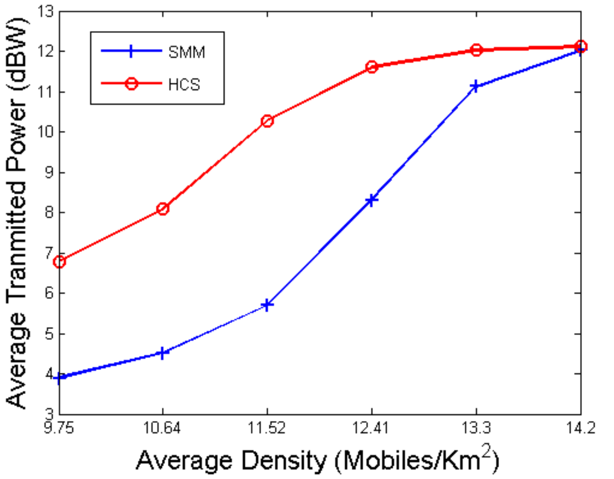

Figure 4. Average transmitted power as a function of the average mobile density in the scenario with asymmetric traffic

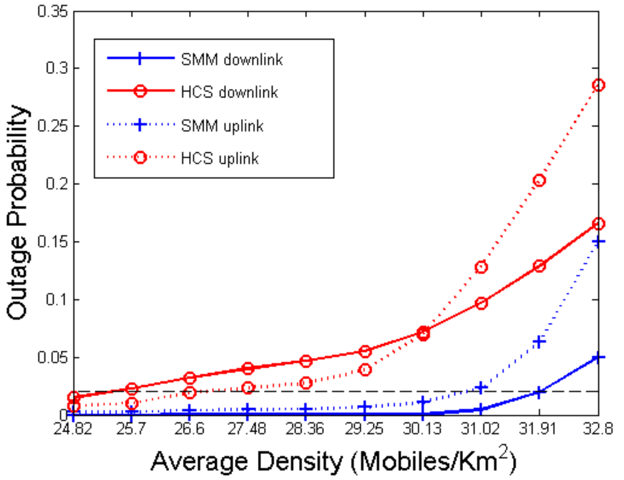

Figure 5. Outage probability as a function of average mobile density in the scenario with symmetric traffic

In Figure 6, we show the total outage probability of the third scenario. In this case also, the SMM increases the capacity by 14%. As in the symmetric scenario, the limiting link direction is uplink for the SMM and downlink for the HCS.

V. Conclusions and Open Issues

In this paper, we proposed a coupling matrix that is able to capture inter-cell interaction in both uplink and downlink. Thereafter, we introduced a practical spectrum management methodology based on this matrix. The proposed methodology takes into account the fact that uplink and downlink frequency carriers cannot be allocated independently. Simulation results for both symmetric and asymmetric services have shown that the proposed methodology outperforms the classical frequency allocation in the HCS in terms of capacity and transmitted power.

The proposed approach can be extended to a dynamic methodology that is able to detect relevant changes and find the suitable frequency allocation dynamically. This is left for future work as well as the case where more than one frequency carrier could be allocated to one base station.

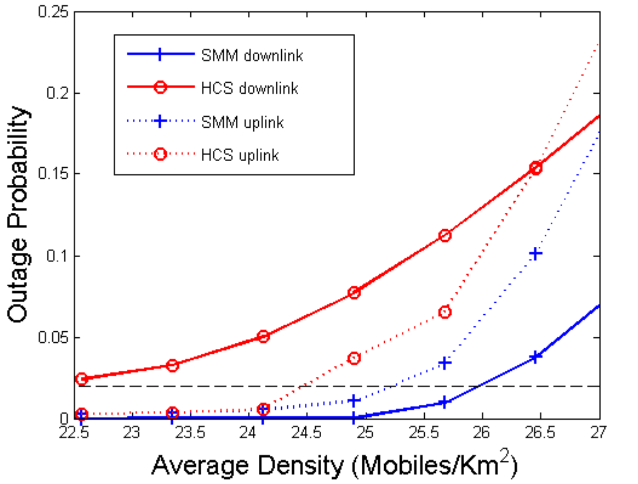

Figure 6. Outage probability as a function of average mobile density in the scenario with symmetric traffic in macro-cells and asymmetric traffic in hotspots

Acknowledgement

This work was partially performed in project E2R II which has received research funding from the Community's Sixth 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 E2R II consortium are hereby acknowledged. This paper is also supported by the COSMOS grant (ref. TEC2004-00518, Spanish Ministry of Science and Education and European Regional Development Fund).

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