Combined Dynamic Channel Assignment and Non-linear Spatial Processing for High Throughput Packet Radio*

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Abstract - **In this work we discuss the use of a dynamic packet to time-slot assignment (DPA) algorithm combined with a non-linear interference suppression method for a TDMA-based network equipped with an antenna array in the base station. Single and multicell cell scenarios are considered. The whole receiver strategy (combined DPA and non-linear spatial processing) is then evaluated for different degrees of spatial diversity. Results show that the combined strategy produces a considerable throughput improvement, especially for a high offered load condition.**

I. INTRODUCTION

As wireless internet access is expected to grow rapidly, the accommodation of the corresponding increased data rates of new emerging applications, over a radio access network, requires highly spectral efficient air interfaces. A large amount of work has been dedicated to expand the ability of handling a large quantity of data traffic in wireless networks by means of enhancing the multi-user capacity. For example, exploiting the spatial diversity provided by an antenna array has shown the potential of increased data rates as resulting from reduced level of system-wide interference [1,2].

However, the benefits introduced by the use of spatial processing in a smart antenna scheme depend on the instantaneous channel characteristics. In other words, the gains introduced by the antenna arrays can vary significantly in the time because of the dynamics of interference in a wireless system. This can be harmful since all the potential of this technology will not be exploited when planning for the worst-case scenario. One way to increase the overall system spectral efficiency is to merge the physical and medium access layers in a joint design. For instance, smart antenna and channel allocation techniques can be combined, allowing a substantial throughput improvement due to a better multi-user compatibility that can be achieved [3,4].

In this work we discuss the use of a dynamic time-slot assignment algorithm for packets transmitted in a TDMA-based network equipped with an antenna array in the base station. The, hereafter called, dynamic packet assignment (DPA) algorithm assigns the users having packets to send to the available time slots in a manner to reduce the co-channel interference among the users. The decisions are taken according to the user's spatial signatures that are assumed to be known by the algorithm. The optimal solution combines the users in such a way that the throughput is maximized. Nevertheless, such a solution is impracticable in real systems due to the high amount of computations needed. Therefore, sub-optimal solutions must be implemented for real time applications.

The adaptive antenna algorithm applied in the base station seeks increased capacity by means of a reduction in the multi-user interference. This is obtained by a combination of conventional linear processing and a non-linear interference suppression method. This latter is based on a successive interference cancellation (SIC) algorithm. The whole receiver strategy (combined DPA and non-linear spatial processing) is then evaluated through computer simulations in single and multicell scenarios under several system configurations.

The rest of this paper is organized as follows: a description of the system is done in section II, the DPA and SIC algorithms are introduced in III and IV respectively, the results are presented in V and we come to conclusions in section VI.

II. SYSTEM DESCRIPTION

A. Signal Model

Consider a packet radio network formed by T cells, each of them with K users and a base station equipped with an M element smart antenna system. The vector of received discrete time signals over the antenna array at a specific cell is given by:

$$\mathbf{r}(n)=\sum_{i=1}^{K} s_i(n).\mathbf{h}_i(n)+\sum_{j=1}^{(T-1).K}\sqrt{P_j}.s_j(n).\mathbf{h}_j(n)+\mathbf{v}(n) \qquad (1)$$

where, $s_i(n)$ is the symbol sent by the ith user at the discrete time n, $\mathbf{h_i}$ is the space-time channel vector, P_j is the jth user long term power and $\mathbf{v}(n)$ is the vector of white gaussian noisy present in the antenna array. Note that the first

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summation corresponds to the intracell users, while the second one represents the other-cell interferers. The space-time channel **h**(t) is defined by the expression :

$$\mathbf{h}(t)=\sum_{g=1}^{G}\alpha_g(t).\delta(t-\tau_g).\mathbf{d}(\theta_g) \qquad (2)$$

where, α_g, τ_g and θ_g are the attenuation, delay and direction of arrival associated to the gth multipath. The vector $\mathbf{d}(\theta_g)$ represents the array response corresponding to a planar wave that arrives from a direction defined by θ_g. In this work, the antenna array is formed by linear equally spaced (LES) elements.

A power control is performed in such a way that the intracell user signals are received with unit power at their serving base stations. According to this affirmation, the other-cell user power P_j can be calculated as:

$$P_j=\frac{d_o^{\gamma}}{f_o}.d_i^{-\gamma}.f_i \qquad (3)$$

where, d_o is the distance between the user j and his/her base station, γ is the distance path loss exponent (n this paper γ = 3.5), f_o is the shadowing attenuation (here modeled as a log-normal variable with standard deviation = 8dB), d_i and f_i are, respectively, the distance and the shadowing between the user j and the cell of interest (in our case, the central one).

The intracell user packets are acquired using a spatial filter. The output signal for the ith user has the form:

$$y_i(n)=\mathbf{w}_i^H(n).\mathbf{r}(n)\,. \qquad (4)$$

The weight vector $\mathbf{w}_i(n)$ is calculated according to the MMSE (Minimum Mean Square Error) criterion. For this sake, a Direct Matrix Inversion Algorithm is applied. A training sequence is used for the weight adjustments.

In this paper, we assume that the desired and interfering user data are independent, identically distributed random variables with zero mean and unit variance. Furthermore, we also consider that the channel is stationary during the time of a frame and that there is no inter-symbol interference.

The channel influence over the network performances is evaluated in terms of its spatial diversity characteristics. Two extreme situations are used for this purpose [Winters]. The first one presents a negligible angular spread, so the signals received in all the antennas are correlated (no diversity case). In the opposite way, we have a scenario with a large spatial diversity degree. In this situation the angular spread is much more important than the first one (diversity case). This corresponds to a very small coherence distance. In other words, we can consider that all antennas suffer independent fading.

B. Media Access Control Protocol

The packet transmissions are coordinated by a combined TDMA-SDMA protocol. In such scheme, the time is divided in frames of fixed length formed by L equal size slots. Each user having a packet to transmit will have one of the L slots allocated to him/her, according to the assignment algorithm, in the beginning of the frames. The exact number of signal transmissions and the corresponding user spatial signatures are, somehow, (e.g. through a polling or a contention phase) available to the DPA algorithm.

The users are uniformly distributed in each cell area. The network is composed by 100 equal size hexagonal cells. As a way to avoid the mirror image problem presented in LES arrays, each cell is divided into three sectors, which are 120° wide.

III. THE DPA ALGORITHM

In order to achieve a better and more homogeneous performance, a DPA algorithm, acting at the MAC layer, coordinates the resource allocation based in the present transmission conditions. Users having packets to transmit are allowed to do so at the beginning of each frame following the DPA algorithm. The slot allocation is based on the signal-to-interference ratio (*SIR*) value of the co-slot users, thus the allocation mechanism try to group the most compatible users in such a way that the co-channel interference level is kept as low as possible, increasing the packet capture probability.

As mentioned earlier in this paper, the co-cell user channels are known. The DPA algorithms use this information to calculate the *SIR* of the desired user as follows:

$$SIR_d=\frac{\mathbf{w}_d^H\mathbf{H}_d\mathbf{w}_d}{\mathbf{w}_d^H\mathbf{H}_u\mathbf{w}_d} \qquad (5)$$

where, SIR_d, $\mathbf{w}_d$ are the signal to interference ratio and the weight vector for the desired user respectively, $\mathbf{H}_d=\mathbf{h}_d.\mathbf{h}_d^H$ and $\mathbf{H}_u$ is the undesired signal correlation matrix:

$$\mathbf{H}_u=\sum_{i=1,i\neq d}^{K-1}\mathbf{h}_i\mathbf{h}_i^H\,. \qquad (6)$$

Note that only the information concerning the intracell users is available for the DPA algorithm.

An optimal solution for the *SINR*-based allocation problem must find the best user combination in order to achieve the greater co-channel interference compatibility. We can easily see that an enormous amount of tests must be performed to accomplish this task. For real time systems, the implementation of such a solution is not reasonable.

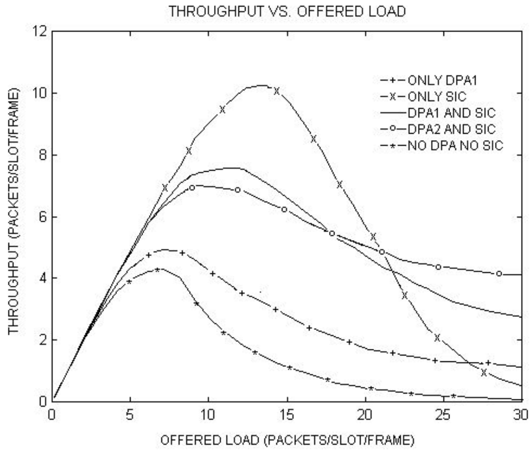

Fig. 1 Performance of DPA and SIC algorithms in a system with a low degree of spatial diversity.

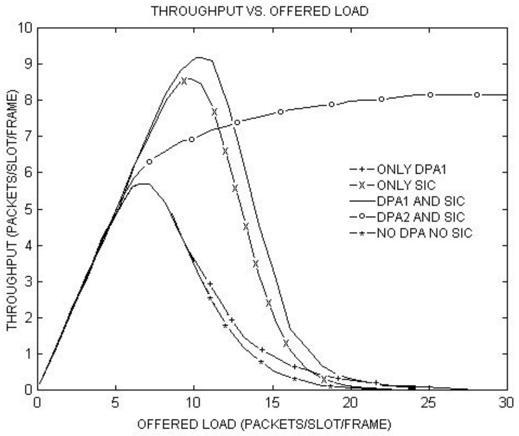

Fig. 2 Performance of DPA and SIC algorithms in a system with a large degree of spatial diversity.

In this work, two sub-optimal *SIR*-based allocation strategies are exploited. The first strategy assigns the L first users to the L free slots. A compatibility test in all slots is made for the next user. The slot where the average *SIR* of all co-slot users is greater will be allocated to the current user. This operation is repeated until the last user is assigned to a slot.

The second strategy is similar to the first one, except for the fact that a user cannot be assigned to a slot if the *SIR* of one or more co-slot users, including the user in consideration, falls below a certain threshold. If this condition is not observed in all slots, the packet will be discarded. This strategy is very useful for high traffic load conditions once it avoids throughput losses due to a strong co-channel interference level.

In this paper the first strategy and the second one will be referenced as DPA-1 and DPA-2, respectively.

IV. THE SIC ALGORITHM

A smart antenna system with linear processing can manage up to M simultaneous transmissions, where M corresponds to the number of elements in the array. To overcome this limit, a non-linear scheme can be employed. The Successive Interference Canceling (SIC) algorithm is one of the most popular techniques for the multi-user interference cancellation. It presents a good performance/complexity ratio when compared to other techniques like Maximum Likelihood Estimation or the Parallel Interference Cancellation [5]. Contrarily to a fully parallel linear MMSE scheme, this algorithm does not estimate all users simultaneously, but does this successively.

The basic idea of this algorithm is to recover the data from one user at a time and to try to eliminate its interference contribution from the received signal vector [5]. First of all, a scheduling based on the *SIR* from all users is made. At every iteration, the user with best *SIR* is handled by the spatial filter, which adapts its weight vector according to the MMSE criterion. The recovered signal is re-modulated and its contribution on the received signal vector is subtracted. These steps are repeated until the demodulation of all users is accomplished. This algorithm works in a slot-basis manner, i.e. the algorithm restarts at the beginning of each slot.

The DPA and the SIC algorithms run at the base station in an independent way. The first coordinates the packet transmission while the second acts at their reception.

V. PERFORMANCE EVALUATION

In this section, we analyze the proposed strategy behaviors in several contexts. The network performance is evaluated by means of its throughput vs. offered load curves. The values of these parameters are determined per frame and per 120° sector. The throughput is defined, in this paper, as the average number of successful transmissions per frame divided by L. Equivalently, the offered load is defined as the average number of packets offered per cell per frame per sector divided by L. Data are collected from the central base station which has a six element (M=6) smart antenna system.

A. Single Cell Environment

The first scenario evaluated consists of a single cell. In Fig. 1 it is shown the throughput vs. offered load curves for an environment without angular spread (no diversity case). In Fig. 2 we have the results for an environment with spatial diversity (diversity case). The DPA-2 threshold was set to 20dB for both cases.

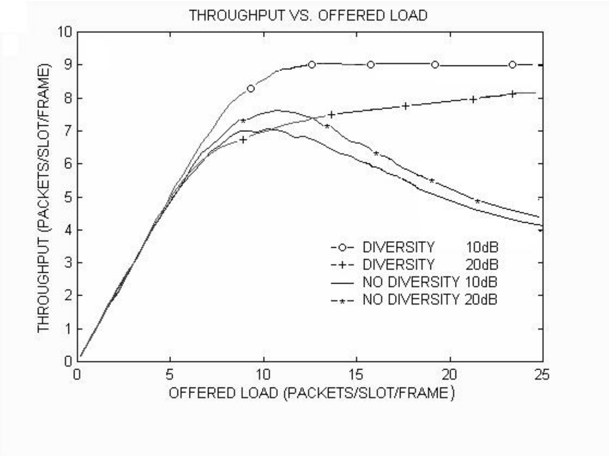

Fig.3 Threshold influence in the combined DPA-2 and SIC algorithm. Diversity and no diversity cases are evaluated.

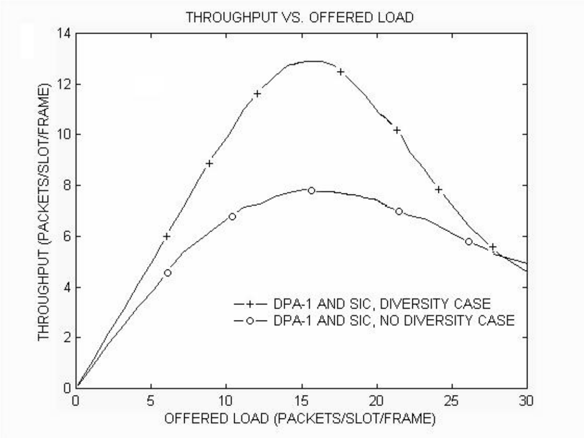

Fig.4 Imperfect power control influence in the combined DPA-1 and SIC algorithms. Diversity and no diversity case are evaluated.

A significant performance difference between the two observed environments can be noticed. The channel spatial diversity effect in the SIC algorithm has already been investigated in [6]. In the diversity case, we verify that the DPA-1 algorithm brings about little throughput improvement in the overloaded region (more packets than antennas), while in the no diversity case, the throughput increase is much more significant. This is due to the fact that in the no diversity case, the user signal arrives from a well-defined direction. Another user will be considered compatible with the first one if they are spatially separable. Thus, the DPA-1 tries to group the most compatible users in each slot. On the other hand, in the diversity case the user signal arrives from multiple directions. There is not a preferential angle of arrival. In this situation, all the users have almost the same compatibility degree. In this context, there is not a great difference between a random scheduling and a *SIR* based one.

Another interesting phenomenon presented in the diversity case is the user *SIR* behavior. When the system goes from an underloaded to an overloaded situation, the *SIR* values for all users fall down abruptly. When even the highest co-slot user *SIR* value is under a certain level, the errors occurrence increases in the first treated users. In that condition, the SIC algorithm does not work correctly due to propagation of eventual error in the first packets to the others. This effect is less noticeable in the no diversity case because in this situation there is almost always a dominant user, i.e. the *SIR* values don't decrease uniformly for all users in such a way that the first user to be handled by algorithm has a much more better *SIR* value than the last one. In other words, the error probability for the first treated user is greater for the diversity case than for the no diversity case, for a same offered load condition. One way to minimize this effect is benefiting the existence of a dominant user. This can be accomplished in a very simple way. Till now, all the simulations were done under the perfect power control assumption. The employing of an imperfect power control mechanism allows the appearance of a dominant user. In Fig. 4, the results concerning this mechanism are presented. The user power is modeled as a lognormal variable with σ^2 = 3dB. The DPA-1 and SIC algorithms are used in a diversity and no diversity contexts. We can see that a considerable improvement in the throughput performance is obtained, especially in the diversity case.

The DPA-2 method ensures that the minimum *SIR* in the system is always above the threshold used as the algorithm parameter. This method combined with the SIC algorithm produces excellent results, especially for high offered load situations, when it converges to a non-zero throughput, contrarily to the other method. This is achieved at the cost of a non-negligible rate of discarded packets.

The threshold for packet discard on DPA-2 must be correctly chosen in order to achieve a better performance. This is illustrated in Fig. 3. Two thresholds are evaluated in this example: 10dB and 20dB. Again an evident difference of behavior can be observed in the two environments in question. While in the diversity case, the threshold changing from 20 dB to 10 dB produces a performance improvement; in the no diversity case the contrary is noticed.

B. Multicell Environment

In this sub-section we observe the inter-cell interference as well as the network asynchronism effects. All the cells have the same offered load characteristics. The 4 and 7 frequency re-use patterns are used.

As mentioned early, the DPA and SIC algorithms exploit only the intracell user information, then the other cell user signals are treated as an unknown interference by the spatial filter which will try to eliminate it. Of course this consumes smart antenna resources, decreasing the capacity to handle the intracell interference. Results shown so far concern a fully synchronized system, that is, the beginning and the end of the time slots in all the cells obey the same time reference.

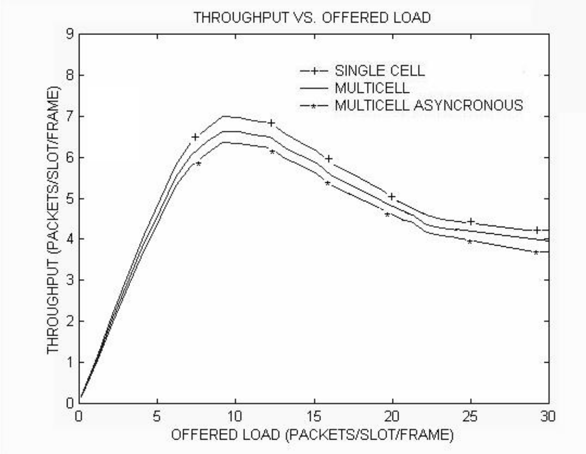

Fig. 5 Combined DPA2 and SIC algorithm in a 7 reuse factor multicell environment. No diversity case.

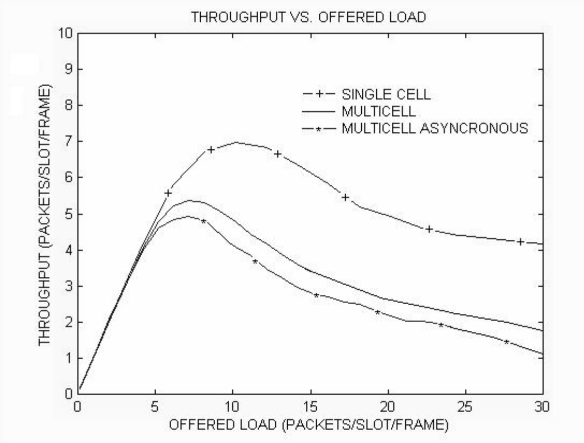

Fig. 6 Combined DPA2 and SIC algorithm in a 4 reuse factor multicell environment. No diversity case.

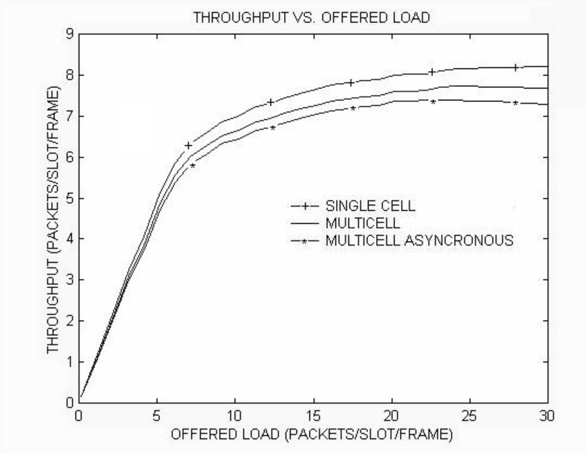

Fig. 7 Combined DPA2 and SIC algorithm in a 7 reuse factor multicell environment. No diversity case.

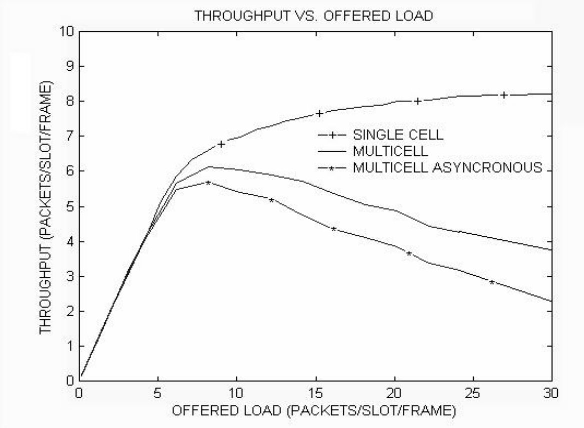

Fig.8 Combined DPA2 and SIC algorithm in a 4 reuse factor multicell environment. Diversity case.

If the synchronism among the cells cannot be implemented, the interference fluctuates during the packet transmission, and therefore the spatial filter will not be able to carry out the interference elimination as well as before. This comes from the fact that the antenna array weight vector is assumed not able to track channel and interference time variations, once they are adjusted during the training phase.

Our model of inter-cell network asynchronism considers that the interference variation occurs abruptly, i.e. the users in an interferer cell are replaced by others with independent transmission characteristics at each time slot. These variations can take place many times in the same time slot and therefore throughput degradation is expected.

The inter-cell interference and the asynchronism effects are shown in Fig. 5 to 8. In these results, we compare the combined DPA2 and SIC algorithm, in a diversity case and no diversity case contexts, in the single cell as well as in the multicell scenario. A 20dB threshold was used for the DPA2 algorithm. As expected, the other cell interference decreases the throughput. This is clearer for the environment with 4 re-use factor, Figs. 6 and 8. In that condition, a more important interference level is observed due to a greater number of interferers as well as their closer proximity to the central base station. The combined DPA2 and SIC algorithm controls the intra cell interference keeping it under a certain level. In a single cell scenario, this permits the throughput to converge to a stable value for high offered loads. In a multicell scenario, as the inter cell interference is not handled by the algorithm, it cannot maintain the total, intra plus inter cell, interference limited. Consequently, the throughput converges to zero as the offered load increases. The asynchronism augments the interference effects. It means that for a same inter-cell interference level the throughput is decreased in relation to the synchronous case. In an analog way, the combined DPA1 and SIC algorithm results, not shown here, have shown similar performance degradation under the same conditions. For a 7 cells re-use pattern configuration, Figs. 4 and 6 show that the performance degradation is significantly less noticeable.

VI. CONCLUSIONS

In this work, we have evaluated the performances of two scheduling algorithms associated to a non-linear interference suppression scheme in a single cell as well as in a multicell environment. The main conclusions taken from this paper are: the spatial diversity degree present in an environment affects strongly the algorithm performances; the DPA1 does not improve significantly the system throughput performance when applied in an environment with a large angular spread; on the other hand the DPA2 combined to the SIC algorithm is capable of sustaining a high throughput over a large range of offered packet load at the cost of a non-negligible packet discard rate; the inter cell interference and the network inter-cell asynchronism cause a severe degeneration in the network performance when the tight cells frequency re-use patterns is employed.

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