Autonomous optimized interference management of CDMA cellular access with multichannel

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Abstract— **We analyze the resource allocation problem for CDMA in a multicell wireless access, by defining an optimization problem for the radio resource assignment, with a twofold aim: first, we try to balance selfish single cell performance with generated interference to surrounding cells; second, we require each Base Station to assign its resources to mobile stations within the cell, by relying only on local data and measurements so that no explicit signalling is required among different cells.**

A specific contribution of this work is to explore the potential of a multichannel approach to the autonomous cell assignment problem, so as to dynamically decouple stations that are too much coupled by interference.

I. INTRODUCTION

Wireless access networks designed for packet traffic and high throughput are a major challenge, boosted by the impressive success of cellular networks and more recently by the massive deployment and speed increase of Wireless Local Area Networks (WLANs).

Frequency bandwidth allocations and often power level limitations point at relatively low power communications with a high degree of flexibility of radio resource management. Non-orthogonal resource sharing seems to be both a source of possible capacity gains in multicell environments and above all the pathway for large scalable distributed wireless networks. Interference becomes the dominant limitation of channel performance. Each transmitting unit generates interference as a function of its transmission power level and of its traffic. This induces an intricate interplay of radio channel transmission at the physical layer and higher layer traffic profiles.

A vast literature addresses the issue of power and possibly rate allocation to a number of interfering links. In particular, a number of works have proposed resource allocation and scheduling schemes for the user transmissions in CDMA systems ([3]-[6]). Such schemes aim at achieving an efficient utilization of the radio resources, by exploiting the soft capacity of CDMA, while at the same time trying to achieve some level of fairness among the users.

We focus on an infrastructured CDMA system, based on Base Stations (BSs), each governing a cell where a number of Mobile Stations (MSs) access the network. We consider the allocation of resources for the uplink; as in other related works, we state a non-linear programming optimization problem for the assignment of power and rate.

The rest of this paper is organized as follows. Section II outlines the main findings of this work. The used model and the optimization problem are stated and solved in Section III. Performance results are given in Section IV, first for a purely CDMA based single channel dynamic access, then the results are extended to a mixed TD-CDMA multi-channel case, by defining an heuristic slot scheduling algorithm.

II. MAIN RESULTS

A major contribution of the present work is the evaluation of an optimization target function aiming at striking a balance between selfish cell metrics (average data delivery delay) and generated interference to other cells.

We do so by taking into account the transmission power as a cost in the objective function of the optimization problem; a weighting parameter can be varied, thus making it possible to achieve more or less aggressive transmission policies. This approach is in part similar to the one followed in [7], [8] for decentralized power control; we apply it to the problem of joint allocation of power and rate operated by BSs in a multicell environment.

Our results show that, through a good choice of the weighting parameter, it is possible to drive the multi-cell system to work in a low power high throughput regime, meaning that the obtained throughput is close to the achievable maximum one, and the average power transmitted is much smaller than the maximum allowed power; fairness is preserved by requiring that the average delay of all backlogged MSs be finite.

A second contribution lies in the preliminary assessment of the benefits brought about by a multichannel scheme coupled with the basic CDMA technique. We show the benefits obtained by having potentially interfering terminals transmit in different channels (time slots, in our case).

III. THE ALLOCATION OF RESOURCES

A. The resource allocator

We consider the uplink of a CDMA cell, containing N users. In the following, we focus on a single cell, but we take into account the interference produced by other cells. We deal with the resource assignment problem from the point of view of a single Base Station (BS), which does not coordinate explicitly with the other BSs, i.e. each BS only relies on local information and measurements.

Our goal is to assign the transmission rates and powers to the backlogged MSs associated to a given BS, for a given scheduling interval. We assume that each user has a Quality of Service (QoS) requirement, given as a lower bound γ_i on the acceptable SIR. Thus we have:

$$SIR_i = \frac{1}{r_i}\frac{g_i p_i}{q + \sum_{j\neq i} \alpha g_j p_j} \geq \gamma_i \quad i = 1, \ldots N \tag{1}$$

where

- q is the total external interference and noise $q = \eta + I$, where η is the thermal noise and I is the interference coming from other cells;
- g_i is the path gain from the i-th MS to the tagged BS;
- p_i is the transmission power of the i-th MS;
- $\frac{1}{r_i}$ is the processing gain, $r_i = \frac{R_i}{W}$ where R_i is the actual transmission rate and W is the chip rate.
- α is the orthogonality factor, which models the effect of a (partial) orthogonality in the spreading codes; we assume $\alpha > 0$.

We impose an upper bound P_{max} on the transmission power of each user, so it must be $0 \leq p_i \leq P_{max}$. Moreover, for each user the bounds $0 \leq r_i \leq 1$ on the normalized transmission rates must hold. An allocation of power and rate within the given constraints is feasible if Equation (1) can be satisfied with equality. The feasibility conditions on the solution of Equation (1) have been derived, for example, in [1]-[2]; we recall them here. Given a rate assignment, the Pareto optimal powers p_i^* under minimum SIR constraints can be written in the form:

$$p_i^* = \frac{r_i\gamma_i}{g_i\left(1+\alpha\gamma_i r_i\right)}\left(\frac{q}{1-\sum_j \frac{\alpha r_j\gamma_j}{1+\alpha r_j\gamma_j}}\right) = \frac{u_i}{g_i\alpha}\frac{q}{1-\sum_j u_j} \tag{2}$$

where $u_i = \frac{\alpha r_i\gamma_i}{1+\alpha r_i\gamma_i}$. We can easily find the conditions on the u_is such that the constraints on rate and power are satisfied:

$$\sum_j u_j + \frac{q}{\alpha g_i P_{max}} u_i \leq 1, \quad i = 1, \ldots N \tag{3a}$$

$$0 \leq u_i \leq \frac{\alpha\gamma_i}{1+\alpha\gamma_i} \tag{3b}$$

B. The optimization problem

Various optimization criteria have been proposed for the uplink scheduling in CDMA systems; see, for example, [1], [4]. Some papers propose a minimization of the sum of assigned powers, given a fixed assigned rate; or a maximization of the (weighted) sum of the rates. We take a different approach, by taking into account the state of the buffers of the transmitting terminals. The issue of fairness must be taken into account; it has been shown that a mere overall throughput optimization brings about extreme unfairness; i.e., some links are effectively shut off. Our goal is to minimize the average data delivery delay, computed on the basis of the current queue lengths, l_i, and of the assigned rates, r_i. Thus we minimize the sum of the delays $d_i = \frac{l_i}{r_i}$. However, we also attempt to strike a balance between an optimal allocation of resources within the cell and the need to limit the interference generated towards other cells, as well as the energy consumption.

Thus we consider the sum of transmission powers as a cost. We have the following problem:

$$\min \sum_i \left(\frac{l_i}{r_i} + \lambda p_i\right) \tag{4a}$$

$$SIR_i \geq \gamma_i \tag{4b}$$

$$0 \leq r_i \leq 1 \tag{4c}$$

$$0 \leq p_i \leq P_{max} \tag{4d}$$

where λ is a weighting parameter $\lambda > 0$. This problem can be rewritten in terms of the u_is as:

$$\min_u \sum_i \left(\frac{\alpha l_i\gamma_i}{u_i} + \frac{\lambda q}{\alpha g_i}\frac{u_i}{1-\sum_j u_j}\right) \tag{5a}$$

$$\sum_j u_j + \frac{q}{\alpha g_i P_{max}} u_i \leq 1 \tag{5b}$$

$$0 \leq u_i \leq \frac{\alpha\gamma_i}{1+\alpha\gamma_i} \tag{5c}$$

We introduce the parameter $\rho = \sum_i u_i < 1$. The resulting optimum solution is a function of ρ; a ρ value is then chosen so as to minimize the target function. We can rewrite our problem as:

$$\min_u \sum_i \left(\frac{\alpha l_i\gamma_i}{u_i} + \frac{\lambda q}{\alpha g_i}\frac{u_i}{1-\rho}\right) \tag{6a}$$

$$\sum_i u_i = \rho \tag{6b}$$

$$0 \leq u_i \leq \min\left(\frac{\alpha\gamma_i}{1+\alpha\gamma_i}, \frac{\alpha g_i P_{max}}{q}\left(1-\rho\right)\right) \equiv U_i \tag{6c}$$

A solution can be found if:

$$\rho \leq \sum_i \min\left(\frac{\alpha\gamma_i}{1+\alpha\gamma_i}, \frac{\alpha g_i P_{max}}{q}\left(1-\rho\right)\right) \tag{7}$$

This condition poses an upper bound on ρ:

$$\rho \in \left(0, \min\left(\sum_i \frac{\alpha\gamma_i}{1+\alpha\gamma_i}, \frac{1}{1+\frac{q}{\alpha P_{max}\sum_i g_i}}\right)\right] \tag{8}$$

A solution to the optimization problem as stated in Equation 6 can be found by using the method of Lagrange multipliers, as shown in the Appendix.

In order to find the global optimum, we must find the value of ρ that minimizes the objective function. We determined this minimum numerically; our numerical trials show that a bisection root finding algorithm converges in a few iterations.

IV. SIMULATION RESULTS

In this section we show the performance of the algorithm described in Section III-A. We consider a CDMA system with many cells sharing the same bandwidth; multiple access can be achieved by using only code division or both time and code division (see Figure 1; in the first drawing, terminals A,B,C,D,E are only code-separated; in the second one, the frame is divided into time slots, and transmissions of different terminals can also be time-separated).

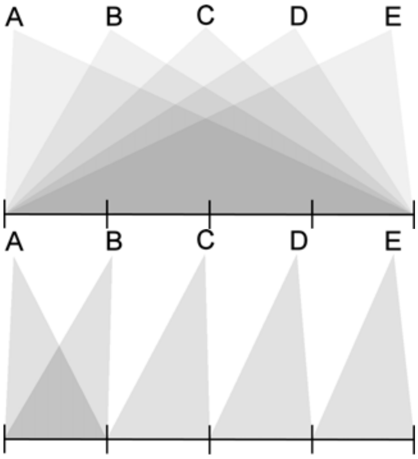

Fig. 1. System using only CDMA and using both CDMA and TDMA

The results we show are obtained in a simulation scenario composed of 7 hexagonal cells (a central cell, surrounded by 6 cells); 100 fixed terminals are uniformly distributed over the area of the 7 cells. Each cell has a radius of $100m$. We simulated a CDMA system, with a chip rate of $54Mb/s$; the frame duration is $32\mu s$. The maximum allowed transmission power P_{max} is $100mW$, and the target SIR is $7dB$.

We first consider a scenario with saturated traffic sources (the buffers of each node are always full); we then simulate a scenario in which the traffic is generated according to independent Poisson processes with a given mean interarrival time identical for all nodes. The packet size is uniformly distributed between 500 and 1500 bytes.

The radio channel has been modeled with a propagation loss proportional to the fourth power of the distance. We assumed that channel gains do not change over time, this is consistent with the assumption of no mobility.

A. Performance with CDMA only (single channel system)

We consider a time axis divided into scheduling intervals (frames) of fixed size. All the terminals can transmit for the whole duration of the frame.

Figure 2 shows the normalized values of the maximum power, the average power and the throughput achieved by the terminals in the central cell, vs. the parameter λ with saturated traffic sources. After a transient phase, the resource assignment freezes on an optimal value depending on the topology and gain matrix. Figure 3 shows, in the same scenario, the sum of the external interference and the thermal noise power, $I + \eta$, normalized to the thermal noise power, η, vs. λ.

Comparing Figures 2 and 3 we can see that, by increasing λ, we are able to achieve high throughput using very low power, as the inter-cell interference decreases with λ. When we assign higher values to λ, the throughput does not immediately decrease; a noticeable decrease starts only when the interference coming from other cells is down to a level comparable with the noise level

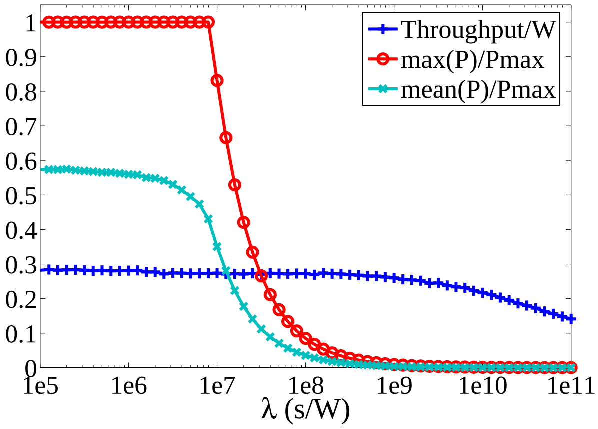

Fig. 2. Normalized throughput and power vs λ under saturation load for the CDMA system

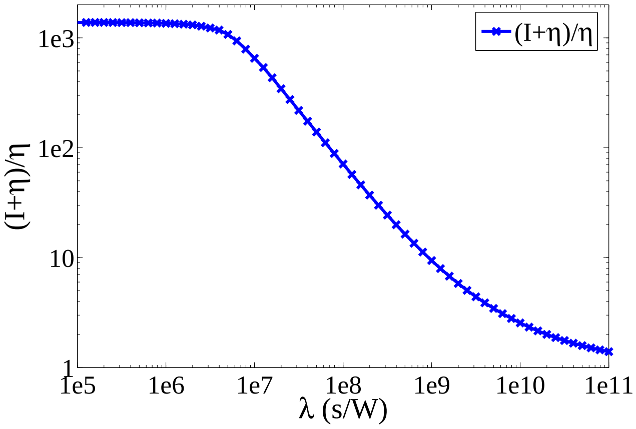

Fig. 3. Normalized external interference vs λ under saturation load for the CDMA system

Figure 4 shows the performance in terms of maximum power, average power, achieved throughput and delay with an offered load of 200 packets/s, as a function of the parameter λ. The results confirm that by a good choice of λ we can drastically reduce power consumption while still maintaining a good throughput.

Figure 5 shows the performance in terms of maximum power, average power, achieved throughput and delay vs. the offered load with $\lambda = 10^8 s/W$.

B. Performance with TD-CDMA

We now consider a TD-CDMA system, with a slotted frame; a given MS is scheduled for transmission in a certain time slot. The channel quality experienced by such a MS depends on the path gain from it to the BS, and on the interference coming from other cells, which varies from slot to slot. We devised a simple heuristic algorithm, trying to reach some degree of fairness, by choosing the time slot so as to compensate the terminals with a lower path gain. The algorithm allocates the terminals with higher path gain (i.e., with a better channel) to

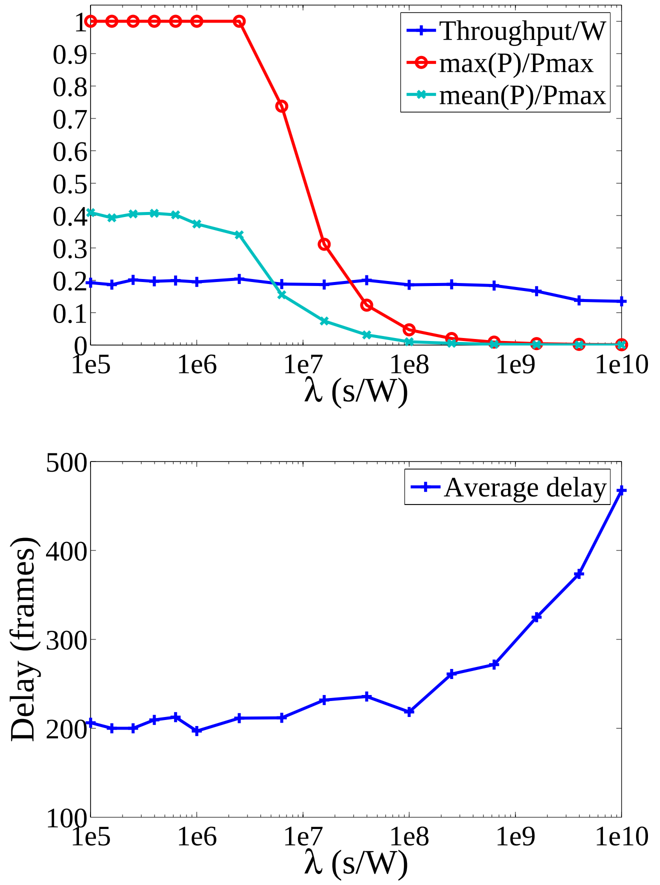

Fig. 4. Normalized throughput, power and delay vs. λ with Poisson traffic for the CDMA system

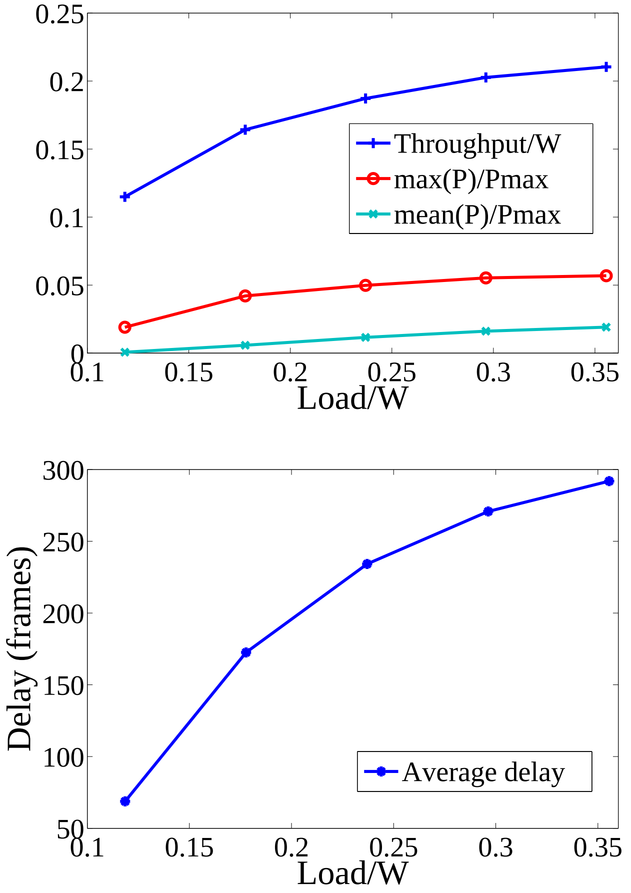

Fig. 5. Normalized throughput, power and delay vs the offered load for the CDMA system

the slots with higher predicted external interference, because such terminals are the ones that can make the best use of these slots. On the other hand the better slots (those with lower predicted external interference) are allocated to the terminals with the lower path gain, which are more affected by interference. It is possible to schedule more than one terminal in a given time slot.

It is important to note that both the selection of the slot (we call it scheduling) and the power/rate allocation need information about the predicted interference in each slot. If, at the beginning of each frame, the scheduler reallocates each terminal using the algorithm just described, the interference changes in every frame and thus cannot be reliably predicted; the whole system will therefore be unstable. For this reason the scheduler chooses the slot to be used by each terminal only for new transmissions, while it maintains the same allocation during a busy period. We also consider the possibility for the scheduler to change the allocation with a given probability p_{change} and to maintain it with the probability $1-p_{change}$. In this way the system will be less stable but it could react to the variations of the external interference caused by transmissions starting anew in the neighboring cells.

As done in Figure 2, in Figure 6 we show the normalized maximum and average power and the normalized throughput achieved by the terminals in the central cell, as function of the optimization parameter λ when each uplink queue is always fully filled.

Comparing Figures 2 and 6 we can see that, by using both TDMA and CDMA, a higher throughput can be reached with lower power consumption; this is due to the time separation of interfering terminals. Observe that this is a way of improving the efficient utilization of the radio resource. Our resource allocator is inherently quite fair, since, due to the formulation of the optimization problem, all the scheduled terminals will necessarily transmit; by coupling it with a scheduler, which distributes the interfering MSs to different channels, we are able to achieve a higher utilization of the bandwidth.

V. CONCLUSIONS AND FUTURE WORK

In this work, we have shown that it is possible to strike a balance between the goal of maximizing the efficient utilization of resources and the goal of minimizing the transmission power. A centralized allocator, controlling many cells, could easily find a convenient value for the weighting parameter λ, allowing terminals to achieve a high throughput while saving power. However, if we exclude explicit signalling among

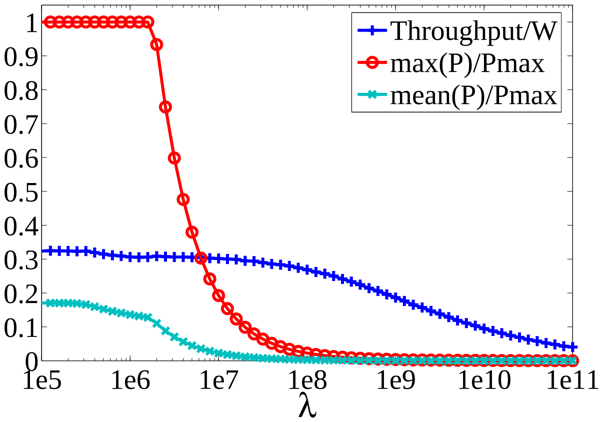

Fig. 6. Normalized throughput and power as function of λ with saturated traffic for the TD-CDMA system with 4 slots

cells, λ must be independently set by each BS. We are now working towards a distributed algorithm, allowing each BS to independently adjust its value of λ.

Our simulations have also shown the benefits brought about by a multichannel scheme, which reduces the number of mutually interfering terminals. The heuristic we devised for the allocation of terminals to time slots is at the moment quite simple, but we are working on its improvement. The idea we aim to prove is that MSs belonging to different cells can autonomously coordinate (without explicit signalling) so that they maintain active links at the same time if the corresponding interference is efficiently sustainable, otherwise they should ”decouple” by going to different orthogonal channels (time-division in this work).

VI. ACKNOWLEDGMENTS

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APPENDIX

The optimization problem in Equation 6 can be solved by introducing a Lagrange multiplier:

$$F\left(\underline{u},\phi\right) = \sum_{i=1}^{N}\left(\frac{\alpha l_i\gamma_i}{u_i} + \frac{\lambda q}{\alpha g_i}\frac{u_i}{1-\rho}\right) + \phi\left(\sum_j u_j - \rho\right) \tag{9}$$

whence:

$$\frac{\partial F}{\partial u_i} = -\frac{\alpha l_i\gamma_i}{u_i^2} + \frac{\lambda q}{\alpha g_i\left(1-\rho\right)} + \phi \tag{10a}$$

$$\frac{\partial^2 F}{\partial u_i \partial u_j} = 0 \qquad i \neq j \tag{10b}$$

$$\frac{\partial^2 F}{\partial u_i^2} = \frac{2\alpha l_i\gamma_i}{u_i^3} > 0 \tag{10c}$$

Thus the Hessian matrix is positive definite, and the extreme value is a minimum. We get:

$$u_i^* = \min\left(\sqrt{\frac{\alpha l_i\gamma_i}{\frac{\lambda q}{\alpha g_i(1-\rho)} + \phi}}, U_i\right) \tag{11}$$

By summing over i we get:

$$\rho = \sum_{i=1}^{N} u_i^* \tag{12}$$

This equation must be solved numerically. From Equations 11 and 12 we see that an upper bound on ϕ can be found when $\lambda = 0$, thus:

$$\phi_{MAX} = \frac{\alpha}{\rho^2}\left(\sum_{i=1}^{N}\sqrt{\gamma_i l_i}\right)^2 \tag{13}$$

A lower bound on ϕ can be found by imposing $\lambda q + \alpha\phi g_i\left(1-\rho\right) > 0$, from which we get:

$$\phi_{min} = \min_i\left(-\frac{\lambda q}{\alpha g_i\left(1-\rho\right)}\right) \tag{14}$$

We can now find the value of $\phi \in \left(\phi_{min}, \phi_{MAX}\right)$ that solves Equation 12. From this we find the u_i^*s.

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