Comparison of Alternatives for Capacity Increase in Multiple-Rate Dual-Class DS/CDMA Systems

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ABSTRACT: Initially this work presents and compares the capacities of multi-cell and power constrained DS/CDMA systems, in the single-class case (voice) with conventional and SIC (successive interference cancellation) detection schemes, determining the maximum number of users for both modes. Next, modelling and results proposed in the literature are extended for multi-cell dual-class systems (voice and data services), comparing the maximum data rates (or data throughputs) obtained with conventional, SIC and scheduling schemes, for some user configurations.

1- Introduction

Third generation mobile communications systems, particularly, DS/CDMA access interface, will be required to support not only speech, but also variable data rate transmission (images, e-mail, file transfer, Internet and corporate network access), video and multimedia services, [1] and [2]. To provide this, they should optimise their capacities and support users with different rates, quality of service, delay and power requirements, [3].

Emerging multi-user detection schemes allow mitigation of the near-far effect and to obtain substantial capacity gains (as will be presented in following sections), [4] and [5]. In this work, particularly, successive interference cancellation (SIC) is analysed due to its simplicity to estimate the received powers directly from the conventional linear correlators' outputs.

The capacity model proposed in [3], for the up-link of a conventional system with variable processing gain, will be extended for the multi-cell case and its capacity for some configurations will be compared in terms of maximum number of users and maximum data rates. This comparison will be done with the capacities achieved by the same system utilising different detection or transmission schemes, namely, SIC and scheduling (the former system will be referred to as “conventional”, in opposition to these two modes). SIC systems capacity modelling was presented in [6] and will also be extended for the multi-cell case. The scheduling scheme that will be analysed was proposed in [7].

Although SIC is a multi-user detection option and scheduling is a different way to transmit data, both can offer capacity gains when compared with conventional systems (which means single user detection with simultaneous transmission by all users), due to reductions in the MAI (multi-access or internal interference). These gains will be compared in this work.

Initially, modelling and results will be presented for a single class case (voice only), next, multi-class, particularly, voice and data (dual class) case will be analysed.

2- Single Class (Voice) Modelling

2.1- Conventional Scheme

As presented in [3], the expression for bit energy (E_b) per total interference power spectral density (I_0), considering perfect power control (that means constant received powers h_iP_i=hP), is given by:

$$\frac{E_b}{I_0} = \gamma_1 = \frac{W}{R_1} \cdot \frac{h \cdot P}{(N-1) \cdot h \cdot P + (\eta_0 + I_E) \cdot W} \qquad (1)$$

In this expression, P_i is the transmission power and h_i is the path loss (*a priori* known) of the i^{th} user, W is the bandwidth, γ_1 and R_1 are rate and QoS (quality of service) requirements for voice, which should be satisfied with equality, N is the number of users in the cell, η_0 and I_E are, respectively, thermal noise and external interference power spectral densities.

For the multi-cell case, given a user configuration in the cell and using the development presented in [8], the normalised cell capacity is given by:

$$\frac{N}{\frac{W}{R_1 \cdot \gamma_1} + 1} = \frac{1}{1+f} \cdot \left\{ 1 - \eta_0 W \Big/ \left[\left(\frac{W}{R_1 \cdot \gamma_1} + 1 \right) \cdot h \cdot P \right] \right\} \le \frac{1}{1+f} \cdot \left\{ 1 - \eta_0 W \Big/ \min_i \left\{ \left(\frac{W}{R_1 \cdot \gamma_1} + 1 \right) \cdot p \cdot h_i \right\} \right\} \qquad (2)$$

where f corresponds to the external (multi-cell) interference impact on cell capacity, as will be detailed next; p is the maximum transmission power constraint for the class and this solution was obtained by taking γ_1 and R_1 equal to their minimum specified values, as mentioned, corresponding to a minimum total power solution, [3]. When the number of users reaches a maximum, the powers will be the maximum allowed ones, but still restricted to the maximum power constraints- for all users- particularly for the most distant user from the cell-site (which corresponds to the minimum $\left(\frac{W}{R_1 \cdot \gamma_1} + 1 \right) \cdot p \cdot h_i$ term).

Using [8] and evaluating the external interference, it follows:

$$f = \frac{I_E \cdot W}{N \cdot h \cdot P} = \frac{1}{\pi \cdot R^2} \cdot \int_0^R r^5 \cdot dr \cdot \sum_{i=1}^{\infty} 6 \cdot i \cdot g(r, 2 \cdot i \cdot R) \approx 0.33 \qquad (3)$$

with: $g(r,d) = \int_0^{2\pi} d\theta \Big/ \left[d^2 + r^2 - 2 \cdot r \cdot d \cdot \cos(\theta) \right]^2$

assuming unity voice activity, propagation losses proportional to the fourth power of distances and homogeneous multi-cell system (identical populations on the cells).

So, the cell capacity, in a multi-cell environment, is reduced to approximately 75% of that corresponding to an isolated cell, due to external interference.

If, furthermore, the capacity is also limited by the total maximum interference level per thermal noise ratio, as described in [9], for the perfect power control case, we can write:

$$\frac{I_0 \cdot W}{\eta_0 \cdot W} = \frac{P_{MAI} + (I_E + \eta_0) \cdot W}{\eta_0 \cdot W} = \frac{(N-1) \cdot hP + (I_E + \eta_0) \cdot W}{\eta_0 \cdot W} \le \frac{1}{\eta} \qquad (4)$$

where P_{MAI} is the total internal (multi-access) interference and η is the cell outage factor, resulting:

$$\frac{N}{\frac{W}{R_1 \cdot \gamma_1}+1} \le \frac{1}{1+f} \cdot \left\{ 1-\eta \Big/ \left[\left(\frac{W}{R_1 \cdot \gamma_1}+1 \right) \cdot \frac{\gamma_1}{W/R_1} \right] \right\} \tag{5}$$

Using (2), it follows:

$$\frac{\eta_0 \cdot W}{p \cdot \min\,(h_i)} = \frac{\eta}{\gamma_1} \cdot (W/R_1) \tag{6}$$

the condition for both capacity limits having the same value.

2.2- SIC Scheme

SIC scheme results in system capacity increase by MAI reduction, performed by successively detecting and cancelling interference from users with stronger powers. It is assumed, in a single class environment, that the received power levels depend only on the users' distances related to the cell-site, neglecting shadowing effects, which means that the users can be ordered, in terms of power, solely by their distances (locations).

Given N users in a cell of radius R, the location probability density of the i^{th} nearest user to the cell-site (i^{th} strongest power) to be in a distance r', inside an interval (r, r+dr) from the cell-site is:

$$f_i(r) = \frac{P_i(r \le r' \le r+dr)}{dr} = \binom{N}{i} \cdot i \cdot \left(\frac{r^2}{R^2} \right)^{i-1} \cdot \frac{2 \cdot r}{R^2} \cdot \left(1 - \frac{r^2}{R^2} \right)^{N-i} \tag{7}$$

This result could be obtained from order statistics of uniform variables, as proposed in [5].

The users' received powers for SIC are disparate and ordered by a control power as follow, [6]:

$$h_i \cdot P_i = \gamma_1' \cdot (\gamma_1' + 1)^{N-i} \cdot P_0 \tag{8}$$

where $\gamma_1' = \frac{\gamma_1}{W/R_1}$ and the power control assures $E_b/I_0=\gamma_1$ for all users, with γ_1 and R_1 the class requirements, as specified. P_0 is given by:

$$\begin{aligned} P_0 &= (I_E + \eta_0) \cdot W = \sum_{\substack{\text{other} \\ \text{cells}}} \sum_{i=1}^{N} \iint h_i P_i \cdot \frac{r^4}{x^4} \cdot f_i(\theta) \cdot f_i(r) \cdot d\theta \cdot dr + \eta_0 \cdot W = \\ &= \sum_{\substack{\text{other} \\ \text{cells}}} \int_0^R P_0 \cdot \frac{\gamma_1' \cdot r^5 \cdot N}{\pi \cdot R^2} \cdot g\,(r,d) \cdot \left[\gamma_1' \cdot \left(1 - \frac{r^2}{R^2} \right) + 1 \right]^{N-1} \cdot dr + \eta_0 \cdot W \end{aligned} \tag{9}$$

where $f_i(\theta)=1/2\pi$ (meaning a uniform probability density of users in θ) and assuming, again, propagation losses proportional to the fourth power of distances.

Comparing with results of the previous section, it follows: $\frac{I_E \cdot W}{(\gamma_1' + 1)^N \cdot P_0} = f$, where f is the capacity reduction factor, due to multi-cell environment, as already presented.

For the worst case multi-access interference (which means the nearest user from the cell-site) the maximum relative total interference bound, as in (4), results:

$$\frac{P_{MAI,1} + P_0}{\eta_0 \cdot W} = \frac{(\gamma_1' + 1)^{N-1} \cdot P_0}{\eta_0 \cdot W} \leq \frac{1}{\eta} \qquad (10)$$

Similarly to (5), the SIC capacity expression is given by:

$$\sum_{\substack{\text{other}\\\text{cells}}} \int_0^R \frac{\gamma_1' \cdot r^5 \cdot N}{\pi \cdot R^2} \cdot g(r,d) \cdot \left[\gamma_1' \cdot \left(1 - \frac{r^2}{R^2}\right) + 1\right]^{N-1} \cdot dr \;\leq\; 1 - (\gamma_1' + 1)^{N-1} \cdot \eta \qquad (11)$$

2.3- Single Class Numerical Results

In (5) and (11), varying η from zero to 0.3 (η can be relaxed, since it corresponds to a soft blocking limitation, as described in [9]), the following maximum numbers of voice users can be obtained with conventional and SIC schemes.

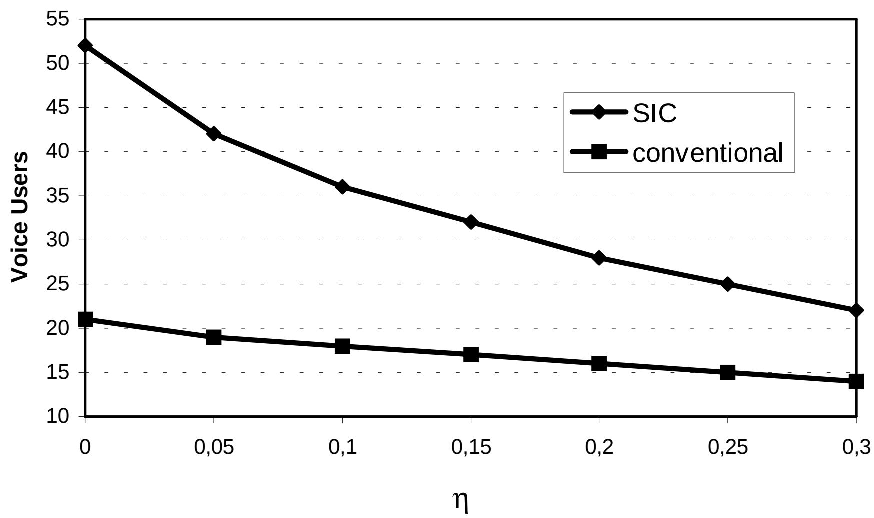

Figure 1: Cell Capacity for Conventional and SIC Systems with Voice Users only
Parameters: W=1,23 MHz; R_1=9,6 kbps; γ_1: 5

It can be observed an increase in capacity with SIC by a factor of two with respect to the conventional mode, as presented in [6], but also, that this factor decreases with η.

3- Dual Class (Voice and Data) Modelling

As proposed in [7], a particular case of multi-class and multi-rates will be analysed:

- Class 1 – voice users

N_1 users, delay intolerants, at constant bit rate R_1, specifying a maximum bit error rate (BER) Pb_1, in terms of γ_1

- Class 2 – data users

N_2 users, delay tolerants, at minimum data rate r_2, specifying a maximum bit error rate (BER) Pb_2, in terms of γ_2.

3.1- Conventional Scheme

From [3] and [8], analogous to the obtained in (2), results:

$$\frac{N_1}{\frac{W}{R_1 \cdot \gamma_1}+1}+\frac{N_2}{\frac{W}{R_2 \cdot \gamma_2}+1} \leq \frac{1}{1+f} \cdot \left\{ 1-\eta_0 \cdot W \middle/ \left[p_2 \cdot \left(\frac{W}{R_2 \cdot \gamma_2}+1 \right) \cdot \min\left\{ h_{2,i} \right\} \right] \right\} \quad (12)$$

where $R_2 \geq r_2$ is the data rate which can be maximised, p_2 is a maximum data user transmission power, Class 2 is assumed to be the more restrictive, $h_{2,i}$ is a Class 2 user path loss and the system is multi-cell and homogeneous with perfect power control and unity voice activity.

The most distant user from the cell-site sets a limit on the maximum value of R_2, because it transmits at maximum transmission power, p_2. In this case (12) becomes an equality.

Note also that a multi-rate perfect power control imposes:

$$h_2 \cdot P_2 = h_1 \cdot P_1 \cdot \left(\frac{W}{R_1 \cdot \gamma_1}+1 \right) \middle/ \left(\frac{W}{R_2 \cdot \gamma_2}+1 \right) \quad (13)$$

The capacity expression can be written also as:

$$(N_1-1) \cdot \gamma_1' + N_2 \cdot \gamma_2' + \left(\gamma_1' \cdot \frac{N_1}{\pi \cdot R^2} + \gamma_2' \cdot \frac{N_2}{\pi \cdot R^2} \right) \cdot \sum_{\substack{\text{other} \\ \text{cells}}} \int_0^R r^5 \cdot g(r,d) \cdot dr \leq 1-\eta \quad (14)$$

for the MAI worst case, which corresponds to a voice user, in the conventional mode.

Similarly to the single class case, we have: $\frac{\eta_0 \cdot W}{p_2 \cdot \min\{h_{2,i}\}} = \frac{\eta}{\gamma'_{2,conv}}$ (15)

Figure 2 shows, for conventional detection, the maximum numbers of data users supported in a multi-cell and dual-class case, depending on power limits given that the data rates were fixed at its minimum value.

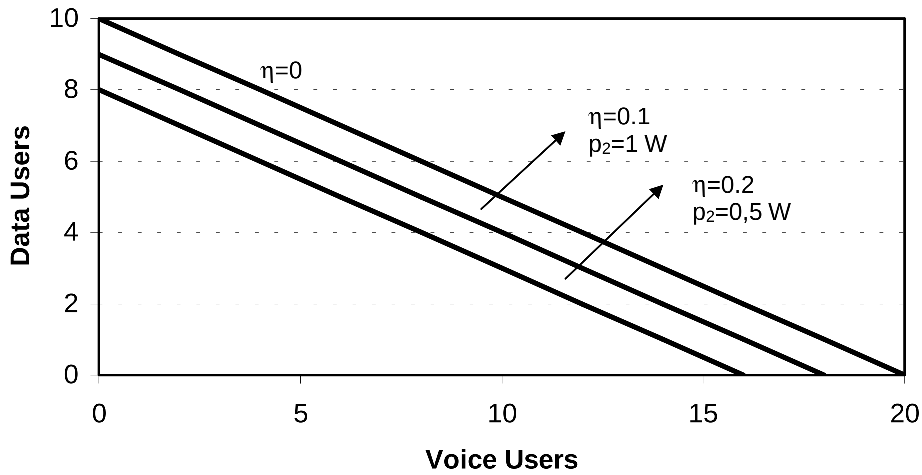

Figure 2: Cell Capacity for a Conventional System with Voice and Data Users versus p_2
Parameters: W=1,23 MHz; R_1=9,6 kbps; γ_1= 5; R_2=14.4 kbps; γ_2= 7; h_{min}=0,1; $\eta_0=10^{-7}$ W/Hz.

This figure shows that dual-class conventional system capacity varies, depending on factor η, which is equivalent to a maximum power limit of the more restrictive class (given thermal noise and path loss parameters), as we can see in (15).

3.2- Scheduling Scheme

Proposed in [7], this transmission scheme allows a MAI reduction using the delay tolerance characteristic of data users, restricting only a limited number $k_2<N_2$ of data users to transmit information at any given instant; the others will be communicating with the base station for synchronisation purposes only, at a low synchronisation rate, or "idle" rate, R_0.

As detailed in the reference, there are conditions for a scheduling gain greater than unity, generated by MAI reduction, to overcome the negative effect of transmission "duty cycles" that appear (k_2/N_2). The scheduling gains also decrease with k_2 and R_0 and increase with the N_2 population. Classes 1 and 2 mean powers needed for the scheduling scheme are the same as those for the conventional mode, but instantaneous Class 2 power used should be N_2/k_2 times greater with the scheduling scheme.

The extended capacity expression, using [8] again, is given by:

$$\frac{N_1}{\frac{W}{R_1 \cdot \gamma_1}+1} + \frac{k_2}{\frac{W}{R_2^* \cdot \gamma_2}+1} + \frac{N_2 - k_2}{\frac{W}{R_0 \cdot \gamma_2}+1} \le \frac{1}{1+f} \cdot \left\{ 1 - \eta_0 \cdot W \middle/ \left[p_2 \cdot \left(\frac{W}{R_2^* \cdot \gamma_2} + 1 \right) \cdot \min\{h_{2,i}\} \right] \right\} \tag{16}$$

where R_2* is the data rate in scheduling mode.

In the maximum throughput solution, also in this case, it is assumed that the most distant data user (given a known configuration) is transmitting at its maximum allowed transmission power.

Figure 3 presents scheduling throughput gains for some configurations, calculated as ratios of maximum data rates per user obtained with scheduling (effective for only a fraction k_2/N_2 of time per user) and maximum data rates per user with conventional mode, supposing it is possible to maximise data rates also in this mode.

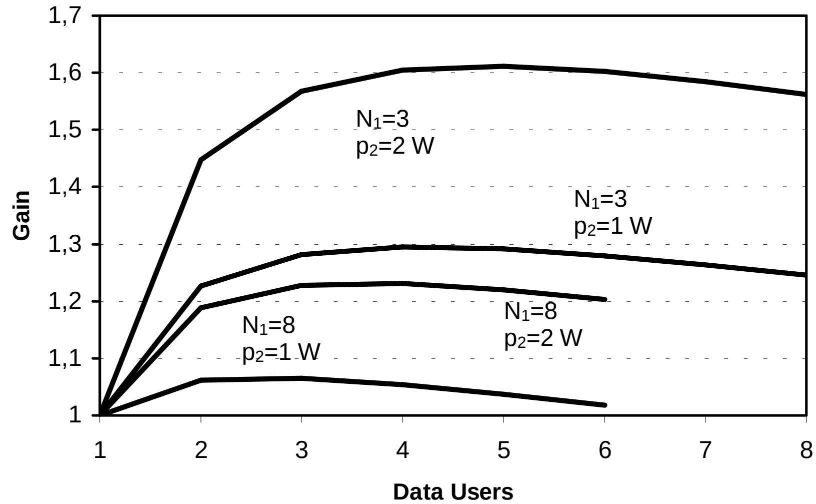

Figure 3: Scheduling Gain versus p_2, Data and Voice Users

Parameters: W=1,23 MHz; R_1=9,6 kbps; γ_1=5; γ_2=7; h_{min}=0,1; $\eta_0=10^{-7}$ W/Hz, R_0=1.2 kbps; k_2=1.

Rate maximisation (and so, capacity) is more limited in conventional mode than in scheduling by the presence of MAI. Variable scheduling throughput gains are exhibited because concerning power limits, scheduling requires greater instantaneous powers, being very sensitive to power limitations.

3.3- SIC Scheme

Assuming data users homogeneously distributed over the cell, but with received power levels in the cell-site greater than those from voice users (due to their rate and QoS requirements that are greater) it can be concluded that the N_2 data users will be detected first, and the ordered powers are [6]:

$$h_i \cdot P_i = \gamma_2' \cdot (\gamma_2' + 1)^{N_2 - i} \cdot (\gamma_1' + 1)^{N_1} \cdot P_{0,\text{total}} \text{, for data users;} \quad (17)$$

$$h_i \cdot P_i = \gamma_1' \cdot (\gamma_1' + 1)^{N_2 - i} \cdot P_{0,\text{total}} \text{, for voice users} \quad (18)$$

With uniformly distributed data and voice users, and using expressions (17) and (18), the multi-cell capacity expression is given by:

$$\sum_{\substack{\text{other}\\\text{cells}}} \int_0^R \frac{\gamma_2' \cdot (\gamma_1' + 1)^{N_1} \cdot r^5 \cdot N_2}{\pi \cdot R^2} \cdot g(r,d) \cdot \left[\gamma_2' \cdot \left(1 - \frac{r^2}{R^2}\right) + 1 \right]^{N_2 - 1} \cdot dr +$$

$$+ \sum_{\substack{\text{other}\\\text{cells}}} \int_0^R \frac{\gamma_1' \cdot r^5 \cdot N_1}{\pi \cdot R^2} \cdot g(r,d) \cdot \left[\gamma_1' \cdot \left(1 - \frac{r^2}{R^2}\right) + 1 \right]^{N_1 - 1} \cdot dr \leq \quad (19)$$

$$\leq 1 - \left\{ (\gamma_2' + 1)^{N_2 - 1} \cdot (\gamma_1' + 1)^{N_1} \right\} \cdot \eta$$

where P_{MAI} was calculated for the nearest user to the cell-site, which is the worst case for SIC.

3.4- Dual Class Numerical Results

Using (14), (15), (16) and (19), maximum data rate values were determined for some configurations for the three schemes, as presented in figures 4 and 5.

Figure 4 compares throughput maximisation gains given by SIC and scheduling for a particular data-class only system. Figure 5 extends these results for dual-class case and two different configurations.

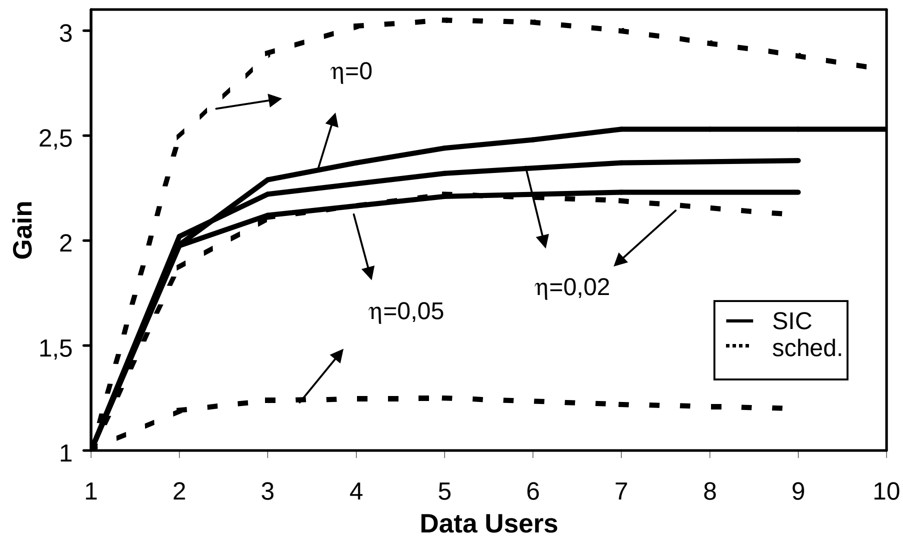

Figure 4: Scheduling and SIC Gains for Data Users only versus η
Parameters: W=1,23 MHz; R_1= 9,6 kbps; γ_1=5; γ_2=7; R_0=1.2 kbps; k_2=1; N_1=0.

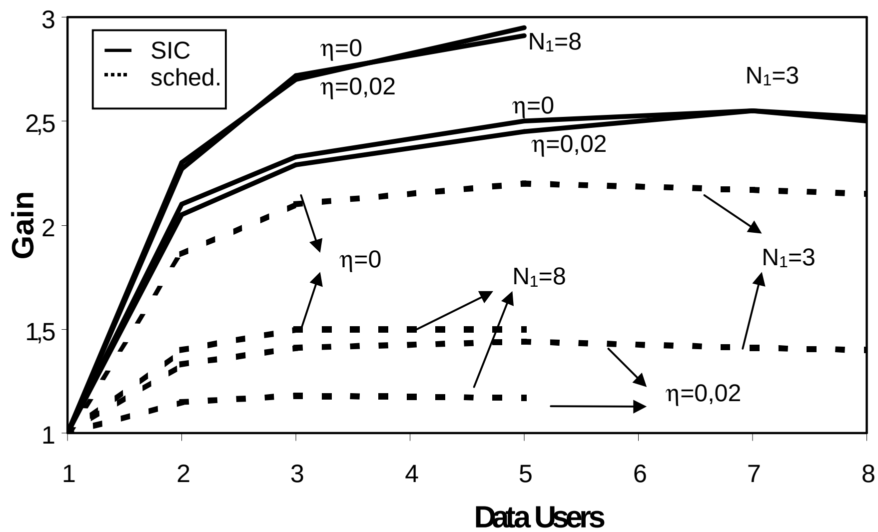

Figure 5: Scheduling and SIC Gains for Voice (N_1 users) and Data Users versus η
Parameters: W=1,23 MHz; R_1= 9,6 kbps; γ_1=5; γ_2=7; R_0=1.2 kbps; k_2=1.

4- Conclusions

The schemes considered in this work can offer substantial throughput gains. The SIC scheme is more stable as a function of η, maintaining gain values around two when calculated for the worst case (nearest user). Scheduling requires higher peak power levels due to its power control and instantaneous power needs and its gains are very dependent on maximum power limits. So we can establish that:

- SIC is better for greater voice user populations or smaller data populations in the cell and also with restricted power levels;

- scheduling is better when it is possible to use higher peak power levels and for mainly data populated systems.

Depending on power levels it is possible to consider a scheduling transmission scheme combined with SIC detection in the same system specially for $k_2>1$. In this case additional gains should be expected.

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