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Ordered Hunt Schemes for Overlaid CDMA Cellular Systems

Esquemas de ordenamiento en sistemas celulares sobrepuestos CDMA

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Abstract

The CDMA overlay concept, has been proposed as one alternative to take advantage of the bandwidth available in narrowband systems. In fact, the basic idea of the CDMA overlay is to allow to wideband CDMA waveforms, to share a common spectrum with narrowband conventional waveforms. In this work, we have focused in the analysis of the performance of the forward link of the CDMA and TDMA systems when they are overlaid. In our model, in order to limit the interference into the CDMA layer caused by the TDMA system, the use of notch filters has been considered. However, one drawback of the filters is that it rejects only one part of the interference generated by the TDMA system. Therefore, we have proposed two new ideas of reduction of the interference which can not be eliminated by filters; ordered hunt and reallocation of the slots. Finally, we present an analytical evaluation of the forward link capacity of the systems involved in the overlaid process, due to this is the limiting link and as a function of the outage probabilities. Practical considerations such as power requirements, power control, handoff, the offered load for different services and scenarios are also addressed.

Keywords: Overlaid system, CDMA performance, TDMA, ordered hunt.

Resumen

La sobreposición CDMA ha sido propuesta como una alternativa para el aprovechamiento del ancho de banda disponible en sistemas de banda angosta. Dentro de este contexto, la sobreposición implica que las formas de onda de banda ancha de un sistema CDMA puedan compartir la misma banda espectral que las formas de onda convencionales de banda angosta. Ahora bien, en este trabajo nos hemos enfocado en presentar el análisis del desempeño del enlace de bajada de un sistema CDMA y TDMA cuando se sobreponen. Con el objeto de limitar la interferencia dentro del sistema CDMA causada por el TDMA, en nuestro modelo estamos considerando la presencia de filtros notch. Sin embargo, una de las desventajas de este tipo de filtros es que solamente eliminan una parte de la interferencia generada por el sistema TDMA. Por lo tanto, hemos propuesto dos ideas

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novedosas que nos permitirán reducir la interferencia que no puede ser eliminada por el uso de filtros, las cuales hemos denominado ordenamiento y reasignación de ranuras. Finalmente, presentamos una evaluación analítica de la capacidad del enlace de bajada de los sistemas involucrados en el proceso de sobreposición, debido a que este es el enlace limitante y en función de la probabilidad de falla. Diversas consideraciones prácticas como requerimientos de potencia, control de potencia, transferencia de llamada cargas de tráfico para diferentes servicios y diferentes escenarios están incluidos.

Descriptores: *sistema sobrepuesto, desempeño CDMA, TDMA, hunt ordenado.*

Introduction

The continuous growth in the traffic volume and the emergence of new services are increasing the rate of change of the wireless networks. To appreciate the growth of the wireless sector; notice that in 1990 only, they existed 10 million of cell phone subscribers mostly using analog FM technology. Today, there are almost one billion of subscribers and it is expected to increase to more than two billion of subscribers in next years. In China alone, more than 15 million cell phone subscribers are being added each month; more than the cumulative number of wireless subscribers that existed throughout the entire world in 1991 [1-3]. With the expected wireless revolution in telecommunications, the efficient use of the available spectrum is crucial. One step in this direction is the spread spectrum overlaid, which could be utilized as an easy migration path toward third generation cellular systems (for example IS-136 to CDMA2000 or GSM to WCDMA).

A big number of authors have explored the performance of the CDMA overlaid systems. For example; one of the first works describe the results of both propagation and field strength measurements, to demonstrate that broadband CDMA waveforms can co-exist in the same frequency band with conventional microwave narrowband system and thus to increase the overall spectral efficiency in that frequency band [4]. However, we have observed that all the experiments and performance analysis have had the following fundamental goals [4-46].

a) Verify that the spread spectrum overlay would not cause excessive interference to the narrowband system.
b) Verify that the spread spectrum system can operate efficiently in the presence of the interference produced by the narrowband system.

In the literature, the overlay problem has been widely explored specially for CDMA systems.

For example, some papers have developed the performance of the overlay of CDMA and microwave systems [5-11]. In others, the performance of the CDMA overlay with FDMA or TDMA systems has been studied in terms of analytical models, which quantify a deterministic SIR ratio for very simplified scenarios [12-18].

In order to successfully implement the overlay of the systems, in a manner such that neither set of users causes excessive interference to the other set; it has been proposed the use of notch filters at the CDMA transmitters and receivers.

A big number of authors have explored the performance of the interference suppression filters in the CDMA overlaid systems [19-39]. Some of these studies have concentrated on quantifying the SIR ratio at the filter output, and others have obtained the bit-error-rate (BER) performance.

As a way to improve the performance of the CDMA overlay, other authors examine the use of multicarrier CDMA [40-44]. Another proposed alternative is the use of frequency-diversity spread spectrum (FD-SS) [12, 44]. One of the most recent proposals is the signal level clipper in the CDMA transmitter and receiver [45-46].

Motivated by the fact that most of the existing works are done partially through measurements, simulations and very simplified analytical models; the first objective of our work is to establish a mathematical model to derive the performance in terms of the Erlang capacity of the overlaid system.

Therefore, we will evaluate the capacity of the overlaid CDMA and TDMA systems considering the Poisson nature of the arrivals, the service activity detection, imperfections on the power control loop, handoff, the effect of the adjacent cell interference, and the use of suppression filters. Our second objective is to show that the interference not rejected by the filters is quite harmful for the overlaid system. Nevertheless, we have proposed a new mechanism to reduce the interference effect, which implies the ordering and reallocation of the TDMA slots[1].

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The paper is organized as follows. In Section II we present the system model and the overlay situation to be considered including the two new proposals. In Section III and IV the performance of the forward link is evaluated. Section V presents numerical results of the capacity estimation for different scenarios. Finally, Section VI gives our conclusions and remarks.

Sistem model

In this work two layers of CDMA and TDMA macrocells are spectrally overlaid. Base stations of both systems are located in the same position and the use of sectored antennas is assumed. The mobile users are uniformly distributed within the cells, and all cells operate at 100% loading.

To make possible the overlay situation, notch filters are placed on the CDMA mobile transmitter and base station receiver. In addition two new proposals are investigated; the ordered hunt and ordered hunt with reallocation of the slots, in order to reduce the probability of occupation of the TDMA co-channel slots (slots inside the CDMA bandwidth) and increase the overlay system capacity. In particular, the ordered hunt scheme assumes that the TDMA slots are numbered 1, 2,…, N_{TS} (N_{TS} is defined as the total available TDMA slots) in a way that co-channel slots are placed at the end of the list. Consequently, each incoming user takes the lowest-numbered idle slot. In the slots reallocation strategy, in addition to which the co-channel TDMA slots are placed at the end of the list, if one slot is set free among the first *m* ordered busy slots the user who occupies the *m-th* slot (final position) will be reallocated to the released position.

The rest of the section will be devoted to the requirements of the CDMA and TDMA systems and to the derivation of the probability density function of the number of active TDMA users inside the W_C bandwidth.

CDMA system

In the CDMA system, the energy to interference ratio requirement denoted by (E_b/I_0), is considered a variable different for each service. In the system, N_S will denote the number of services present in the spreading bandwidth, W_C. Thus, the transmission rate R_k and the required $(E_b/I_0)_{k(req)}$ define the *k*th class of service for $1<k<N_S$. In the CDMA system the co-channel interference received from the outside of the cell will be modeled as f_C times the total power received from the intra-cell, in the forward link (f_C is defined as the other cell interference factor). Some other important assumptions are:

a) A log-normal random variable, $\ _k$ (with parameters of its characteristic Gaussian random variable, mean m_k and standard deviation $\ _k$), will model the variable $(E_b/I_0)_k$ of each user. Then, some typical values are, $\ _k$=1.5dB and $m_k=(E_b/I_0)_{k(req)}$ [50-52].
b) The number of active calls for each class of service *k* is modeled through a Poisson random variable, with mean the offered load denoted by $(\ /\ )_{C(k)}=a_{C(k)}$. In previous equation, is the arrival rate, and is the call duration.
c) The activity factor for each *k* class of service is modeled as a binary distributed random variable, $\ _k$, with $P(\ _k=1)=\ _k$.

TDMA system

In the TDMA system we consider a frequency reuse factor K_T, it means that the total system bandwidth will be divided in K_T groups of frequency, each one consisting of a number of channels separated in frequency. Therefore, we assume that the TDMA system supports a maximum of N_{TS} users per sector, given by

$$N_{TS} \quad \frac{B_T n_T}{_s K_T B_{TS}} \tag{1}$$

where B_T is the TDMA available bandwidth, n_T is the number of TDMA time slots per carrier, K_T is the reuse factor of the TDMA system, B_{TS} is the bandwidth of a TDMA channel and *s* corresponds to the number of sectors on the system. Each sector has N_{TS} time slots of which n_{TSC} slots are in the W_C bandwidth, that is, n_{TSC} are the co-channel time slots for the CDMA system. Depending on the W_C bandwidth we have different values of the parameter n_{TSC} as we can see on table 1.

Table 1. n_{TSC} TDMA Slots

B_T	W_C bandwidth	Number of n_{TSC} slots
12.5 MHz (n_T 3 and K_T 7)	1.2288 MHz	6
	3.6864 MHz	18
	7.3728 MHz	36

1 The overlay problem with ordering and reallocation is partially based on previous works [47-49].

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In the TDMA system the total bit rate per user is R_T kbps in an equivalent bandwidth of $W_T = B_{TS}/n_T$ [17, 18]. Thus, we can conclude that the total TDMA co-channel interference bandwidth is given by $W_{Tcoc} = sK_T W_T n_T$.

In the proposed system model, it is assumed that the CDMA bandwidth is completely overlaid by the TDMA system. This setup corresponds to a situation of practical interest in which the overlay could be utilized as an easy migration path toward third generation cellular systems; for example, IS-136 to CDMA2000 or GSM to WCDMA [14–15, 18–24].

Like the frequency bands of the narrow band interference are known, the CDMA system can reduce the interference produced by or toward the TDMA system by employing notch filters at the CDMA receivers or transmitters respectively (figure 1).

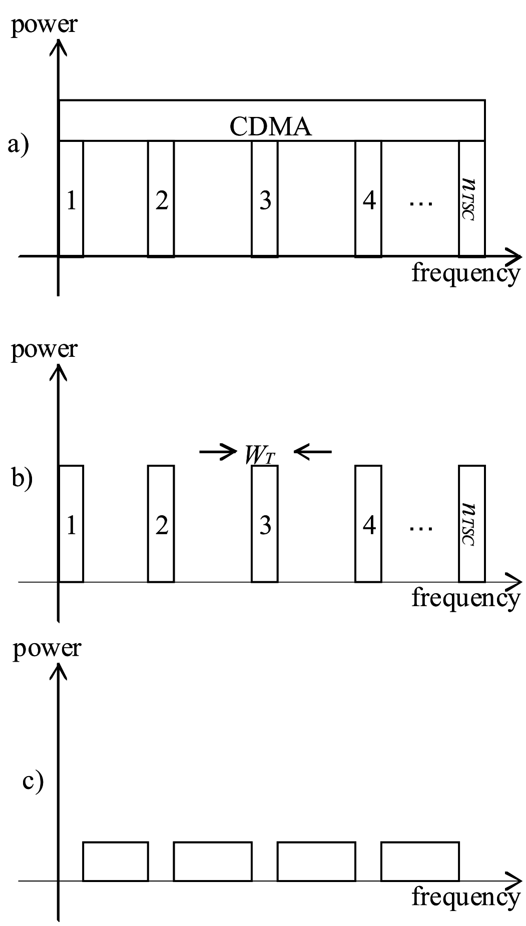

Figure 1. Frequency distribution of the CDMA and TDMA overlaid system. a) CDMA wideband and frequency bands of the TDMA slots. b) TDMA interfering frequency bands. c) Cut frequencies of the notch filters

However, such filters also reduce the effective available spread bandwidth of the CDMA system. If a fraction p of the original available spread bandwidth of the CDMA system is filtered, the resulting effective CDMA bandwidth is

$$W_{Cef} = W_C(1 - p), \tag{2}$$

wherein, for ideal notch filters $p = (n_{TSC} * W_T)/W_C$. From the CDMA cell of interest, each TDMA cell except the co-channel cells has a different group of n_{TSC} interfering slots, in this manner, the use of notch filters can reduce the interference produced by TDMA system only on the desired and co-channel cells (in the evaluation we assume an effective co-channel TDMA bandwidth $W_{Tcoc,ef}$ which excludes the frequency bands assigned to the desired and co-channel cells).

The same situation occurs from the TDMA cell point of view, where the interference only is reduced in the CDMA cells that overlap the desired and co-channel TDMA cells.

TDMA without ordered hunt

The proposed TDMA system has N_{TS} available slots per sector, from which n_{TSC} slots are inside the W_C bandwidth. Therefore, the probability density function of the number of active TDMA users, N_T, inside the W_C bandwidth denoted as $P(N_T = q)$ for $0 \le q \le n_{TSC}$, is expressed as

$$P(N_T = q) = \sum_{j=q}^{L} P\,(\text{from } N_{TS} \text{ slots } j \text{ are bussy, } N_T = q \text{ slots of } j \text{ are inside } W_C) \tag{3}$$

where L is the maximum occupancy for $N_T = q$, which is given by $(N_{TS} - n_{TSC}) + q$; $\bar{n}_{TSC} = N_{TS} - n_{TSC}$ are the slots outside of the W_C bandwidth, therefore in (3) we have

P(from N_{TS} slots j are bussy, $N_T = q$ slots of j are inside W_C) =

P(from N_{TS} slots j are bussy)P($N_T = q$ slots of j are inside W_C/from N_{TS} slots j are bussy) =

$$\frac{a_T^j / j!}{\sum_{k=0}^{N_{TS}} a_T^k / k!} \cdot \frac{\dfrac{\bar{n}_{TSC}!}{(j-q)!(\bar{n}_{TSC} - j + q)!} \cdot \dfrac{n_{TSC}!}{q!(n_{TSC} - q)!}}{\dbinom{N_{TS}}{j}} \tag{4}$$

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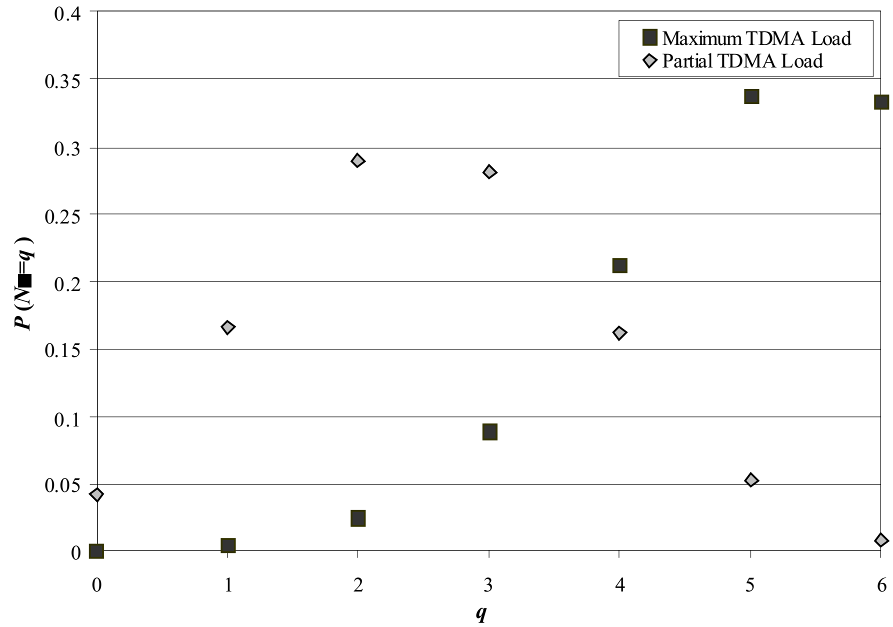

Figure 2. Probability density function of N_T for a_T=48.7Erl and a_T=25Erl, considering a normal slots allocation and W_C=1.2288MHz

where a_T is the TDMA load given by the product of the arrival rate, λ_T, and the mean service time, $1/\mu_T$. In figure 2 we show the probability density function of N_T for two different TDMA loads and for W_C=1.2288MHz. Notice that when the TDMA load increases the probability of occupation of the TDMA co-channel slots also increases. Thus, it was necessary to reduce the TDMA load until values that would make possible the operation of the overlaid system. Therefore we have evaluated two different load conditions

a) The maximum TDMA load that the system can offer for a blocking probability of 2%, given by a_T=48.7 Erl.
b) One scenario in which we have approximately one half of the maximum load (partial value), given by a_T=25Erl. This value originates a blocking probability of 3.0135e-009.

Finally, the probability that the q-th slot is busy is [53]

$$P(q-th \text{ slot is busy}) = \frac{a_T[1-B(N_{TS},a_T)]}{N_{TS}} \quad (5)$$

wherein $B(N_{TS},a_T)$ is the Erlang loss formula for N_{TS} busy slots.

TDMA with ordered hunt

For the ordered hunt scheme we assume that the TDMA slots are numbered 1, 2,…,N_{TS} in a way that co-channel slots are placed at the end of the list, and each incoming user takes the lowest-numbered idle slot. Thus, we can model the slot occupancy as a Markov chain with $2N_{TS}$ states, as we can see in figure 3, wherein the general macrostate E_u represents the number of busy slots in the system, for u=0,…,N_{TS}. The microstates of the form (0,0,…,0) represent all the possible positions of occupancy of u slots. Then for u=0, the state (0,0,…,0) represents the non-occupancy of the slots. For u=1 the states (1,0,…,0) to (0,0,…,1) models the occupancy of one slot, from the first position to the final position. We follow in this way until the value, $u=N_{TS}$, for which the state (1,1,…,1) models the occupancy of all the slots. In general, each E_u is integrated by a group

$$\binom{N_{TS}}{u} = \frac{N_{TS}!}{u!(N_{TS}-u)!}$$

of states, which are representing all the possible positions of occupancy of u slots.

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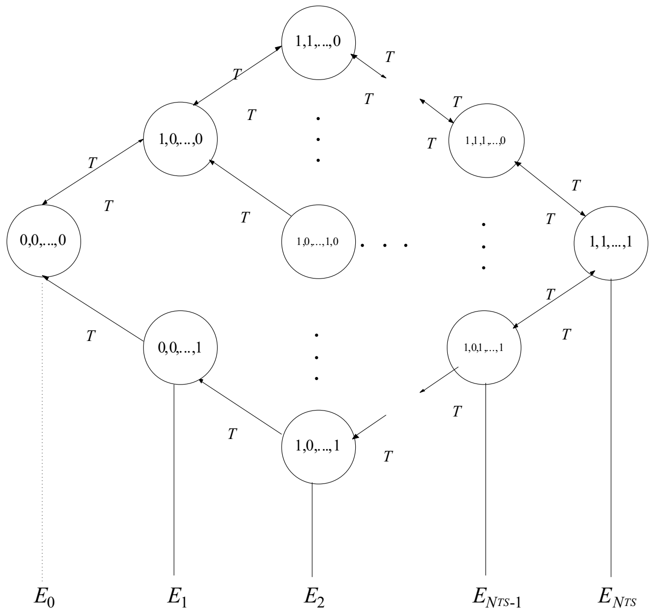

Figure 3. Markov chain model for TDMA system with ordered hunt

We can model this ordering through the Markov chains of figure 3, from which we find the probability density function of the number of active TDMA users inside the W_C bandwidth. Therefore, the $P(N_T=q)$, is found directly from the probability of being in each microstate.

$$P(N_T \quad q)$$

$$P\begin{pmatrix}\text{Non of the co} \quad \text{channel} \\ \text{slot is busy}\end{pmatrix} \qquad P\begin{pmatrix}q \text{ co} \quad \text{channel} \\ \text{slots are busy}\end{pmatrix} \tag{6}$$

$$P(0,\ldots\vec{0},0\ldots,0) \ \ldots \ P(1,\ldots,\vec{1},0,\ldots,0) \quad q \quad 0$$

$$P(0,\ldots,\vec{0},1,\ldots,0) \ \ldots \ P(1,\ldots,\vec{1},1,\ldots1) \quad 0 \quad q \quad n_{TSC}$$

where the mark indicates the position of the last non co-channel slot given by the difference N_{TS}-n_{TSC}. In (6) the probability to be in each microstate was obtained with a simulation because the analytical solution is not tractable. Figure 4 shows the $P(N_T=q)$ considering ordered hunt, for maximum and partial TDMA loads. As we can observe, especially for the partial TDMA load the occupation probability of the non co-channel slots is drastically incremented. Associated to this we have an improvement of the system performance.

Finally, in the ordered hunt [53]

$$P(q \quad th \text{ slot is busy}) = a_T[B(q \quad 1, a_T) \quad B(q, a_T)] \tag{7}$$

where a_T is the TDMA load and $B(q,a_T)$ is the Erlang loss formula for q ordered busy slots.

TDMA with ordered hunt and reallocation of the slots

In the slots reallocation strategy the co-channel TDMA slots are placed at the end of the list, but if one slot is set free among the first m ordered busy slots the user who occupies the *m-th* slot (final position) will be reallocated to the released position. In this strategy, as we force to the system to remain in the microstates (0,0,…,0), (1,0,…,0), (1,1,…,0),…,(1,1,…,1) the system can be modeled with a Markov chain with $N_{TS}+1$ states.

As we can see in figure 5, each microstate corresponds with the general macrostate $E_0,\ldots,E_{NTS}$ of an Erlang loss system.

Hence, we find that the probability density function of the random variable, N_T, is given by

$$P(N_T \quad q)$$

$$P\begin{pmatrix}\text{Non of the co} \quad \text{channel} \\ \text{slots are busy}\end{pmatrix} \quad \sum_{r \ 0}^{N_{TS} \ n_{TSC}} B(r, a_T) \quad q \quad 0$$

$$P\begin{pmatrix}q \text{ co} \quad \text{channel} \\ \text{slots are busy}\end{pmatrix} \quad B(q, a_T) \quad 0 \quad q \quad n_{TSC} \tag{8}$$

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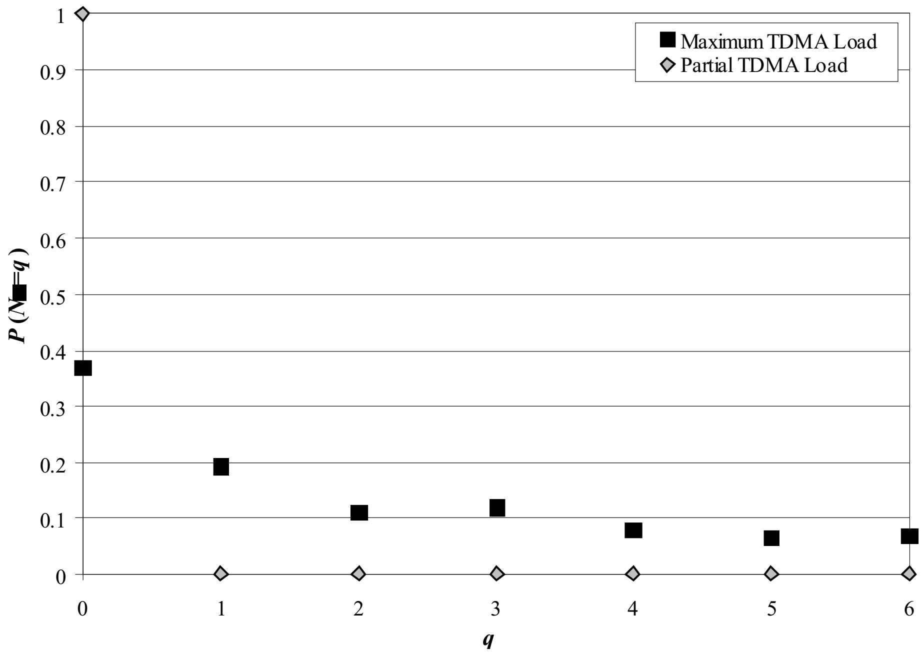

Figure 4. Probability density function of N_T for a_T=48.7Erl and a_T=25Erl, considering ordered hunt and W_C=1.2288MHz

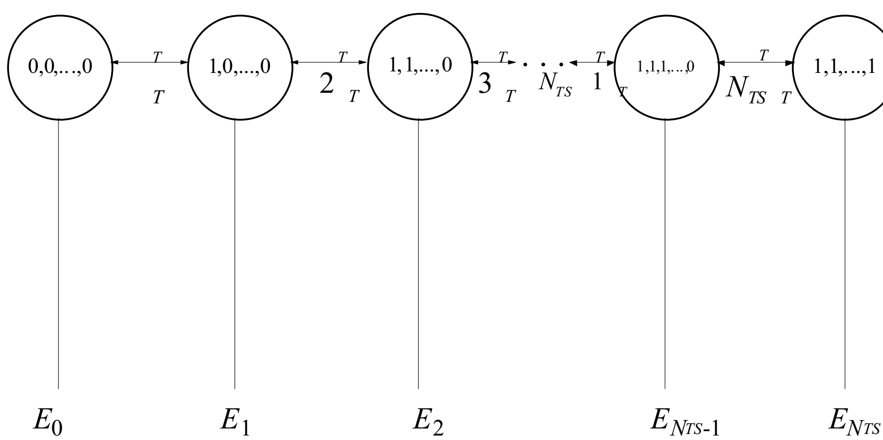

Figure 5. Markov chain model for TDMA system with ordered hunt and reallocation of the slots

where $B(q,a_T)$ is the Erlang-B formula, given by

$$B(q,a_T) = \frac{a_T^q / q!}{\sum_{r=0}^{N_{TS}} a_T^r / r!} \tag{9}$$

for a_T the TDMA load. Figure 6 shows the probability density function of the number of active TDMA users. Notice that due to the reallocation strategy the occupation probability of non co-channel slots is incremented in comparison with the previous schemes.

Additionally, we have that

$$P(q\ th\ \text{slot is busy}) = \sum_{r=q}^{N_{TS}} B(r,a_T), \tag{10}$$

where $B(r,a_T)$ is the Erlang-B formula.

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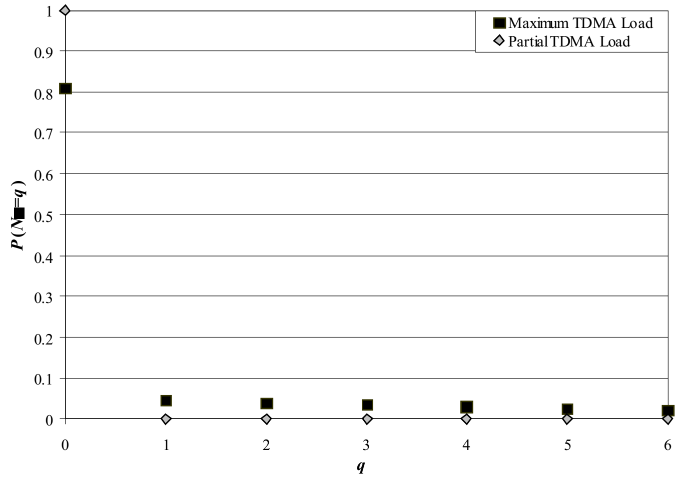

Figure 6. Probability density function of N_T for a_T=48.7Erl and a_T=25Erl, considering ordered hunt and reallocation of slots and W_C=1.2288MHz

Forward link performance

CDMA performance

The forward link capacity depends on the power that is available for the traffic channels [54-56]. Typically, the power allocation to each overhead channel is determined from experimental tests. To maximize the capacity of the forward link, it is essential to control the power of the cell in order to allocate the power to an individual mobile according to its needs. Then, for the user 1 of the service $k=i$, the received bit energy to interference density ratio will be

$$\frac{E_b}{I_0}_{i(1)} \qquad \frac{(W_{Cef}/R_i)c^0_{i(1)}}{I_{C,C}W_{Cef} \quad I_{C,T}W_{Tcoc,ef} \quad N_0W_{Cef}}, \tag{11}$$

where W_{Cef} is the effective spreading bandwidth, R_i is the transmission rate of the i-th class of service, $c^0_{i(1)}$ is the fraction of the total power received by user 1 of class i from the 0-th base station. $I_{C,C}W_{Cef}$ and $I_{C,T}W_{Tef}$ are the interference power in the CDMA user due to CDMA and TDMA base stations respectively and N_0W_C is the power of the thermal noise. In (11) we have

$$I_{C.C}W_{Cef} \quad F_{i(1)} \sum_{j\;2}^{N_i} c^0_{i(j)} \quad \sum_{\substack{k\;1\\k\;i}}^{N_S}\sum_{j\;1}^{N_k} c^0_{k(j)} \quad I_{other(1)} \tag{12}$$

where $F_{i(1)}$ represents the impact of the loss of orthogonally at user 1 of class i in the downlink and $F_{i(1)}$ [0,1]. This term is often referred as the multipath loss factor of the radio channel [54-56], and it is the measure of the degree of orthogonally among the own cell signals received by a particular user. Hence, $F_{i(1)}=0$ indicates that the orthogonally of the own cell signal is maintained at the receiver, while $0<F_{i(1)}$ 1 corresponds to the case where the orthogonally is partly or fully destroyed. N_S and N_{BS} are the number of services and the number of interfering base stations included in the system, respectively. N_i and N_k are the CDMA users of the i-th and k-th service modeled as Poisson random variables. $I_{otheri(1)}$ is the individual other cell interference at user 1 of class i. We assume that the fraction of the total power received by user 1 from its CDMA control power base station is

$$c^0_{i(j)} \quad {}_{i(1)} \sum_{j\;2}^{N_i} c^0_{i(j)} \quad \sum_{\substack{k\;1\\k\;1}}^{N_S}\sum_{j\;1}^{N_k} c^0_{k(j)} \quad {}_{i(1)}c_0, \tag{13}$$

where ${}_{i(1)}$ is the downlink resource consumption of user 1 of class i and c_0 is the total power received by user 1 from its CDMA power control base station.

The interference power in the CDMA user due to TDMA base stations is given by

$$I_{C,T}W_{Tcoc,ef} \quad \sum_{L\;1}^{N_{BS}\;N_{BS,COC}}\sum_{j\;1}^{N_T} T^l_{(j)} \tag{14}$$

where $T^l_{(j)}$ is the power designed to the j-th user on the l-th TDMA base station received by user 1 of class i.

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N_{BS}-$N_{BS,coc}$ is the number of interfering base stations included in the system.

Solving (11) with (12), (13) and (14), we have the following result for $_{i(1)}$

$$_{i(1)} \quad \left(\frac{E_b}{I_0}\right)_{i(1)} \frac{R_i}{W_{Cef}} \quad F_{i(1)} \quad f_{i(1)} \sum_{i \; 0}^{N_{BS}} \sum_{j \; 1}^{N_T} \frac{t^{l}_{(j)}}{c_0}, \qquad (15)$$

where $f_{i(1)}$ is the forward link other cell interference factor for the user 1 of class i. In practical systems, a fraction of the total transmitted power is devoted to the pilot channel and other common control channels destined to all users. We assume this overhead as (1-). Therefore, the remaining fraction of the total power is then allocated to all users controlled by the base station in the sector. The system will be in an outage situation if the total allocated transmission power exceeds the total available power at the base station. Then, let us define the system outage probability of the forward link as [54-56]

$$P^{forward}_{o,C} \quad P \sum_{k \; 1}^{Ns} \sum_{j \; 1}^{Nk} {}_{j(k)} v_{j(k)}$$

$$P \sum_{k \; 1|}^{Ns} \sum_{j \; 1}^{Nk} v_{k(j)} \left(\frac{E_b}{I_0}\right)_{k(j)} \frac{R_i}{W_C}$$

$$F_{i(j)} \quad f_{i(j)} \sum_{i \; 0}^{N_{BS}} \sum_{j \; 1}^{N_T} \frac{t^{l}_{(j)}}{c_0} \qquad P(Z \quad), \qquad (16)$$

where $_k$ is the activity of the users of the k-th service class modeled as a binary random variable and $(E_b/I_0)_{k(j)}=E_{x(j)}$ is a log-normal random variable that defines the required (E_b/I_0) of the j-th user of the k-th service class. Using the central limit theorem in (16), Z can be approximated as a Gaussian random variable. Since $f_{i(j)}$ depends on the position of the users, we approximate the estimation by taking the average at all the locations in the sector. Thus, the outage probability is given by

$$P^{forward}_{o,C} \quad Q \frac{\quad E\{Z\}}{\sqrt{Var\{Z\}}} \qquad (17)$$

where is the fraction of the total transmitted power dedicated to the traffic channels, typically between 71% and 80% [55]. Soft handoff on the forward link makes the power allocation even more complicated. For simplicity, we assume that a fraction $g<1$ of all users is in soft handoff and a maximum of three base stations involved in the process [54]. For each user in soft handoff, we assume that the base stations involved allocate the same power fraction to that user. Then, the number of users in each cell is increased by $2g$ because of soft handoff.

The values $E\{Z\}$ and $Var\{Z\}$ are the following

$$E\{Z\} \quad \sum_{k \; 1}^{N_S} a_{C(k)}(1 \quad 2g) \; _k \frac{R_k}{W_{Cef}}$$

$$\exp \quad _k{}^2/2 \quad \exp(\; m_k) \quad F \quad f^{forward}_{C} \frac{1 \quad 2p}{1 \quad p} \quad E \frac{I_{C,T} W_{Tcoc,ef}}{c_0}$$

$$Var\{Z\} \quad \sum_{k \; 1}^{N_S} a_{C(k)}(1 \quad 2g) \; _k \frac{R_k}{W_{Cef}}$$

$$\exp(2(\quad _k)^2)\exp(2 \quad m_k)$$

$$F \quad f^{forward}_{C} \frac{1 \quad 2p}{1 \quad p}^{2}$$

$$2 \quad F \quad f^{forward}_{C} \frac{1 \quad 2p}{1 \quad p} \quad E \frac{I_{C,T} W_{Tcoc,ef}}{c_0}$$

$$E \frac{I_{C,T} W_{Tcoc,ef}}{c_0}^{2} \qquad (18)$$

where $a_{C(k)}(1+2g)$ is the traffic load of the CDMA system, $_k$ is the activity factor of the k-th class of service, $=\ln(10)/10$, $_k=1.5$ dB, $m_k=(E_b/I_0)_{k(req)}$, $f^{forward}_{C}$ is the other-cell interference factor of the CDMA system. For the case in which we use notch filters, the other-cell interference factor is affected by $(1 \quad 2p/1 \quad p)$. F is the impact of the loss of orthogonally whose value depends on the specific scenario, e.g. F=0.4 in a vehicular scenario and F=0.06 in a pedestrian scenario [54].

In (18), the values $E\{I_{C,T} W_{Tcoc,ef}/c_0\}$ and $E\{(I_{C,T} W_{Tcoc,ef}/c_0)^2\}$ are obtained assuming two different scenarios; the TDMA system without power control and with power control.

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We have that the received power on the interest CDMA user from the l-th BS is

$$T^{l}_{(j)\;NPC} \quad \frac{P_{T(j)}}{(r_1^l)\;\;10^{\;\;l/10}} \quad \frac{P_T}{(r_1^l)\;\;10^{\;\;l/10}} \text{ and}$$

$$T^{l}_{(j)\;PC} \quad \frac{\overline{P}^{l}_{T(j)}}{(r_1^l)\;\;10^{\;\;l/10}}, \tag{19}$$

where P_T is the transmitted power by the TDMA base station per user, and $(r_1^l)\;\;10^{\;\;l/10}$ models the propagation losses given by the product of the -th power of the distance between the CDMA interest user and the l-th base station and a log-normal component representing shadowing losses where $_0$ is the dB attenuation with zero mean and standard deviation . $\overline{P}^{l}_{T(j)}$ is the average TDMA transmitted power by the l-th base station which power controls to the j-th user, and which is given by

$$\overline{P}^{l}_{T(j)} \quad e^{\frac{2\;\;\;2}{2}} \quad \underset{B\;S_l}{} P_T\,(r^{l}_{(j)}) \;\; f(a)da \tag{20}$$

where $r^{l}_{(j)}$ is the distance between the l-th base station and all the possible positions of the j-th TDMA user inside of the coverage area of the l-th BS and $f(a) \quad 1/\,cell$ area.

Let us assume a log-normal approximation for the value by the Schwartz and Yeh method. Then in equation (18) we have

$$E \; \frac{I_{C,T}W_{Tcoc,ef}}{c_0} \quad E\{Y\} \quad \exp \quad S\{y\}^{\;2}\,/2)\exp(\;E(y)$$

$$E \; \frac{I_{C,T}W_{Tcoc,ef}}{c_0}^{\;2} \quad E\{Y^2\}$$

$$\exp(2(\;S\{y\})^2)\exp(2\;E(y)) \tag{21}$$

where $E\{y\}$ and $S\{y\}$ are the mean and standard deviation of the random variable which characterize to Y and change in accordance to the non power control scheme or power control scheme used in the TDMA layer.

CDMA Performance

As the outage probability of the forward link, (17), is a function of the position of the CDMA user of interest, we have obtained an average over a large set of mobile positions inside its coverage area. Then

$$P^{forward}_{o,C} \quad \frac{1}{Max} \sum_{i\;1}^{Max} P^{forward}_{o,C}\,(x_i\,, y_i), \tag{22}$$

where Max is the total number of mobile positions.

TDMA performance

For the TDMA system we evaluate the probability of not having an adequate signal to interference ratio, $SIR_{T(req)}$, known as the outage probability. Hence, the outage probability due to the q-th slot is busy, is given by

$$P^{reverse}_{o,T} \quad P(SIR_T \quad SIR_{T(req)}\,/\,q \quad th\text{ slot is busy})$$

$$P(q \quad th\text{ slot is busy}) \tag{23}$$

where in accordance with the slots allocation scheme we can know the P(q-th slot is busy). Then, we follow to obtaining

$$P(SIR_T \quad SIR_{T(req)}\,/\,q \quad th\text{ slot is busy})$$

$$P \;\; \frac{T_D}{I_{T,T}W_T \quad I_{T,C}W_{Cef}} \quad SIR_{T(req)} \quad , \tag{24}$$

where T_D is the power of the desired signal on the TDMA system, $I_{T,T}W_T$ and $I_{T,C}W_{Cef}$, are the powers of the interference in the TDMA system due to TDMA and CDMA systems respectively.

In (24)

$$I_{T,C}W_{Cef} \quad \frac{W_T}{W_{Cef}} \sum_{l\;1}^{N_{BS}} \sum^{N_{BS,coc}} \sum_{k\;1}^{N_S} \sum_{j\;1}^{N_k} v^{l}_{k(j)} \;\; {}^{l}_{k(j)} R_k\,(I_0)_k \tag{25}$$

where N_k is a Poisson random variable which models the CDMA active users. $v^{l}_{k(j)}$ and ${}^{l}_{k(j)}$ are a binary and log-normal random variables which defines the activity of the services and the (E_b/I_0) of the j-th user of the k-th class of service in the l-th base station respectively. R_k is the bit rate requirement of the k-th service and $(I_0)_k$ is the CDMA interference spectral density for the k-th service. W_T is the equivalent TDMA slot bandwidth and W_{Cef} is the effective spreading bandwidth. Again, the evaluation of (24) is conditioned to the consideration or not of power control in the TDMA layer.

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TDMA System without and with power control

Without power control

$$\frac{T_D}{I_{T,T}W_T \quad I_{T,C}W_{Cef}}_{NPC}$$

$$\frac{\dfrac{P_T}{r^0_{0(q)} \quad 10^{\;^0_{0(q)}/10}}}{\sum_{l\;1}^{N_{BS}} \dfrac{P_T}{(r^l_{0(q)}) \quad 10^{\;^0_{0(q)}/10}} \quad \dfrac{W_T}{W_{Cef}} \sum_{l\;1}^{N_{BS}} \sum^{N_{BS,coc}} \sum_{k\;1}^{N_S} \sum_{j\;1}^{N_k} v^l_{k(J)} \;^l_{k(j)} R_k (I_0)_k}$$

$$\frac{\dfrac{1}{r^{\,0}_{\;0\,(q)} \quad 10^{\;^0_{0(q)}/10}}}{\sum_{l\;1}^{N_{BS,coc}} \dfrac{1}{(r^l_{0(q)}) \quad 10^{\;^1_{0(q)}/10}} \quad \dfrac{W_T}{W_{Cef}} \sum_{l\;1}^{N_{BS}} \sum^{N_{BS,coc}} \sum_{k\;1}^{N_S} \sum_{j\;1}^{N_k} v^l_{k(J)} \;^l_{k(j)} R_k \quad _{(NPC)k}}$$

$$\frac{X_{NPC}}{Z_{NPC} \quad Y_{NPC}}, \tag{26}$$

where $_{(NPC)k}$ is the ratio between CDMA spectral interference density received in the base station for the k-th service and the TDMA transmitted signal power. Additionally in (26) we have approximated X_{NPC} by a log-normal random variable, whose characteristic Gaussian random variable has the mean and standard deviation

$$E\{x_{NPC}\} \quad 101\log_{10} \frac{1}{(r^{\,0}_{\;0\,(i)}} \quad \text{and } S\{x_{NPC}\} \tag{27}$$

The random variable Z_{NPC} is approximated as a Gaussian random variable invoking the central limit theorem and Y_{NPC} by a log-normal random variable using the Schwartz and Yeh method. Therefore

$$P \quad \frac{X_{NPC}}{Z_{NPC} \quad Y_{NPC}} \quad SIR_{T(req)} \qquad \frac{e^{\;u^2/2}}{\sqrt{2}} \quad \frac{e^{\;v^2/2}}{\sqrt{2}} Q \tag{28}$$

$$\frac{10^{\frac{uS\{x_{NPC}\} \quad E\{x_{NPC}\}}{10}} \Big/ SIR_{T(req)} \quad 10^{\frac{vS\{z_{NPC}\} \quad E\{z_{NPC}\}}{10}} \quad E\{Y_{NPC}\}}{\sqrt{Var\{Y_{NPC}\}}} \; dvdu$$

where $E\{z_{NPC}\}$ and $S\{z_{NPC}\}$ are the mean and standard deviation of the Gaussian random variable which characterize to Z_{NPC}. The $E\{Y_{NPC}\}$ and $Var\{Y_{NPC}\}$are given by

$$E\{Y_{NPC}\} \quad f_C^{forward} \frac{W_T}{w_{Cef}} \sum_{k\;1}^{N_s} a_{C(k)} (1 \quad 2g)$$

$$_k R_k \quad _{NPC\;k} \exp\,(\quad _k)^2/2 \quad \exp(\;\; m_k)$$

$$Var\{Y_{NPC}\} \quad f_C^{forward} \left(\frac{W_T}{W_{Cef}}\right)^2 \sum_{k\;1}^{N_S} a_{C(k)} (1 \quad 2g)$$

$$_k R_k^2 \quad _{(NPC)k}{}^2 \exp(2(\quad _k)^2) \exp(2 \;\; m_k) \tag{29}$$

where $_{(NPC)k}$ is the ratio between the CDMA spectral interference density received in the mobile for the k-th service and the TDMA base station transmitted signal power.

With power control in the TDMA layer we have

$$P \quad \frac{1}{Z_{PC} \quad Y_{NC}} \quad SIR_{T(req)} \qquad \frac{e^{\;u^2\!/2}}{\sqrt{2}} Q$$

$$\frac{1\Big/ SIR_{T(req)} \quad 10^{\frac{vS\{z_{PC}\} \quad E\{z_{PC}\}}{10}} \quad E\{Y_{PC}\}}{\sqrt{Var\{Y_{PC}\}}} \; du \tag{30}$$

where $E\{z_{PC}\}$ and $S\{z_{PC}\}$ are the mean and standard deviation of the random variable which characterize to the log-normal variable Z_{PC} obtained by Schwartz and Yeh method.

The $E\{Y_{NPC}\}$ and $Var\{Y_{NPC}\}$are given by

$$E\{Y_{PC}\} \quad f_C^{forward} \frac{W_T}{w_{Cef}} \sum_{k\;1}^{N_s} a_{C(k)} (1 \quad 2g)$$

$$_k R_k \quad _{PC\;k} \exp\,(\quad _k)^2/2 \quad \exp(\;\; m_k)$$

$$Var\{Y_{PC}\} \quad f_C^{forward} \left(\frac{W_T}{W_{Cef}}\right)^2 \sum_{k\;1}^{N_S} a_{C(k)} (1 \quad 2g)$$

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$$ _k R_k^2 \quad _{(PC)k}{}^2 \exp(2(\quad _k)^2) \exp(2 \quad m_k), \tag{31}$$

where $_{(PC)k}$ is the ratio between the CDMA spectral interference density received in the mobile for the k-th service and the TDMA base station received signal power.

TDMA performance

The outage probability is a function of the position of the CDMA user of interest. Therefore, we have obtained an average over a large set of mobile positions inside its coverage area, then

$$\bar{P}_{o,T}^{down} \quad \frac{1}{Max} \sum_{i \; 1}^{Max} P_{o,T}^{down}(x_i, y_i) \tag{32}$$

where is the total number of mobile positions.

Numerical results

In this section, we evaluate the performance of the forward link of the CDMA and TDMA overlaid system. All of our evaluations consider different values of the ratios and , the service time on the TDMA layer equal to 2 minutes, =8dB, =4, $f_C^{forward}$ =0.3632 (when 3 BS are participating in the soft handoff) and all the parameters listed on the table 2.

In the numerical evaluations we have considered two different settings, the TDMA layer with and with no power control. Also, we have considered four modes of evaluation of the overlaid system. In the mode 1, it has been evaluated the isolated CDMA or TDMA systems. In the mode 2, it has been evaluated the overlaid system which is operating with the normal allocation of the slots in the TDMA layer. In the mode 3, it has been evaluated the overlaid system when it implements ordered hunt in the allocation of the TDMA slots. Finally in the mode 4, it has been evaluated the overlaid system when the TDMA layer implements the ordered hunt and reallocation of the slots.

We evaluate the performance of the CDMA system for two types of services in the presence of the TDMA system. We have considered a maximum capacity in the CDMA layer given by, a_{Voice}=16.44 Erl and a_{Data}=1 Erl for a blocking probability of around 2%. The TDMA system has been evaluated when it operates at a tolerable capacity, a_T=25 Erl for a blocking probability less than 2%.

Table 3 show the CDMA and TDMA power requirements for different values of the and ratios. As we mentioned previously and ratios, depend on the link and the power control, and are given as parameters. In the forward link without power control on the TDMA layer, $_{NPC}$ is the ratio between the transmitted power by the TDMA base station per user and the total power received by CDMA user from its CDMA power control base station and $_{(NPC)k}$ is the ratio between the CDMA spectral interference density received in the mobile for the k-th service and the TDMA base station transmitted signal power.

With power control on the TDMA layer, $_{PC}$ is the ratio between the average transmitted power by the TDMA base station per user and the total power received by CDMA user from its CDMA power control base station, and $_{(PC)K}$ is the ratio between the CDMA spectral interference density received in the mobile for the k-th service and the TDMA base station transmitted signal power.

Table 2. CDMA and TDMA System Parameters [56]

	CDMA	TDMA
Channel spacing	W_C 1.2288MHz	W_T 10 kHz
Time slot structure	N/A	N_{TS}=59 Reuse factor 7 in a bandwidth of 12.5 MHz
Co-channel time slots	N/A	1.2288 MHz/n_{TSC}=6
Voice Service	$(E_b/I_0)_{(req)}$=5.4dB =0.375 R=8Kbps	$SIR_{T(req)}$=17dB R=16Kbps
Data Services LCD 64k	$(E_b/I_0)_{(req)}$=3.8dB =1 R=64Kbps	N/A
Power control	Yes	Yes/No
Cell Size	1km	1Km

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Table 3. Forward Link Required Transmitted and Received Powers on the TDMA and CDMA Systems for Different and Values

	NPC	PC	(NPC)Voice	(NPC)Dat	(PC)Voice	(PC)Dat
P_{TDMAtx} (BS)=17.04W P_{TDMArx} (Mobile)=1.70E-11W P_{CDMAtx} (BS)=3.55W P_{CDMArx} (Mobile)=3.55E-12W	4.8E12	4.8	4.14E-18	1.39E-18	4.14E-6	1.39E-6
P_{TDMAtx} (BS)=8.52W P_{TDMArx} (Mobile)=8.52E-12W P_{CDMAtx} (BS)=3.55W P_{CDMArx} (Mobile)=3.55E-12W	2.4E12	2.4	8.27E-18	2.78E-18	8.27E-6	2.78E-6
P_{TDMAtx} (BS)=3.55W P_{TDMArx} (Mobile)=3.55E-12W P_{CDMAtx} (BS)=3.55W P_{CDMArx} (Mobile)=3.55E-12W	1E12	1	1.98E-17	6.67E-18	1.98E-5	6.67E-6
P_{TDMAtx} (BS)=1.775W P_{TDMArx} (Mobile)=1.78E-12W P_{CDMAtx} (BS)=3.55W P_{CDMArx} (Mobile)=3.55E-12W	5E11	0.5	3.974E-17	1.33E-17	3.97E-5	1.33E-5
P_{TDMAtx} (BS)=0.7384W P_{TDMArx} (Mobile)=7.38E-13W P_{CDMAtx} (BS)=3.55W P_{CDMArx} (Mobile)=3.55E-12W	2.08E11	0.2083	9.54-17	3.2E17	9.54-5	3.2E-5

In table 3 as a way to approximate the parameter , we assume that the maximum tolerable CDMA spectral interference density is given by $I^{k}_{0(\max)} \quad P_{CDMArx} / R_k) / (E_b / I_0)_k$. Where R_k and $(E_b / I_0)_k$ are the bit rate and the required bit energy to interference density ratio.

No power control on the TDMA layer: Forward link performance

For this macrocell scenario, the performance of the overlaid system when it has maximum load in the TDMA layer is poor, therefore in those conditions it is impossible the operation of the system. Figures 7 and 8 show the CDMA and TDMA performance of the forward link for two classes of services in the presence of the TDMA system when a_T=25Erl, for a blocking probability of 2% in CDMA layer and less than 2% in TDMA layer.

Notice that, although for the normal allocation of the slots the operation of the system is impossible due to the poor performance; we can observe that in the CDMA layer in agreement the ratio g decreases, we have a better performance of the overlaid system because of the reduction in the TDMA transmitted power or the increment in the CDMA transmitted power. The same situation occurs with the ratio , in agreement this undergoes a decrement, the TDMA layer has a better TDMA performance.

A significantly improve on the performance of the overlaid system is observed when the system implements the ordered hunt or slots reallocation strategies.

Power control on the TDMA layer: Forward link performance

Figures 9 and 10 show the performance of the CDMA and TDMA layers when we consider the partial load condition and power control in the TDMA layer. Because of the power control in the TDMA layer, the operation of the overlaid system under more realistic conditions in terms of power requirements and quality levels is possible for both strategies, ordered hunt and reallocation of the slots.

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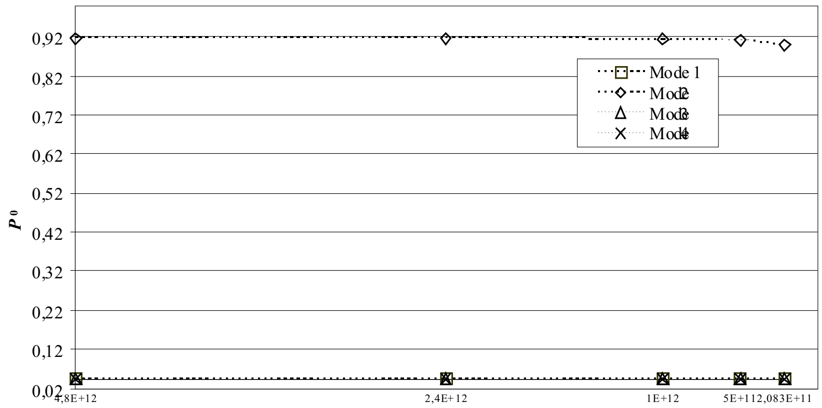

Figure 7. Forward link CDMA performance for a partial TDMA load a_T=25Erl without power control on the TDMA layer

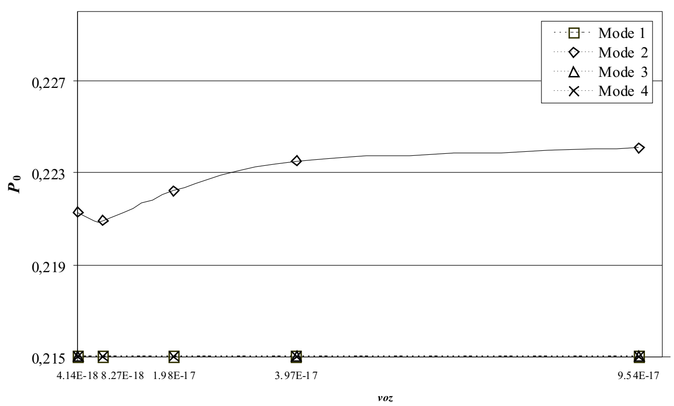

Figure 8. Forward link TDMA performance for a partial TDMA load a_T=25Erl without power control on the TDMA layer

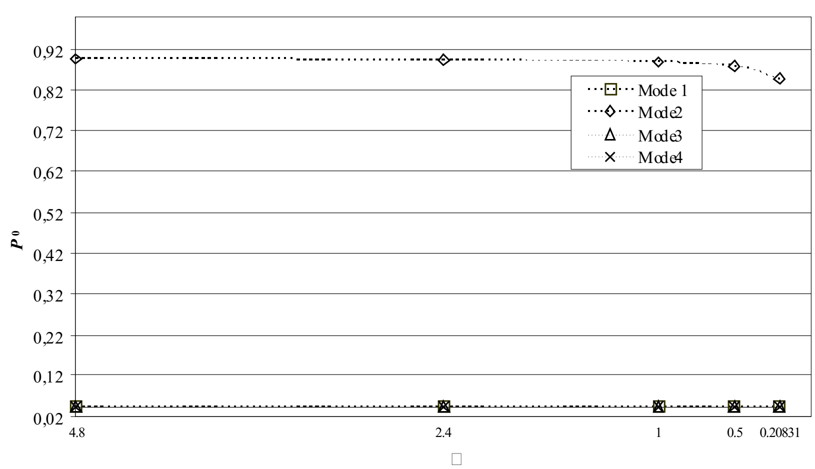

Figure 9. Forward link CDMA performance for a partial TDMA load a_T=25Erl with power control on the TDMA layer

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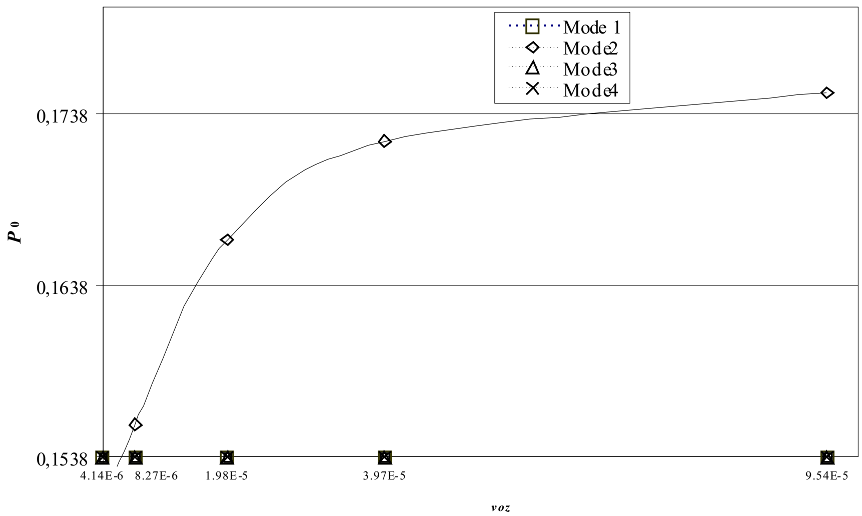

Figure 10. Forward link TDMA performance for a partial TDMA load a_T=25Erl with power control on the TDMA layer

Capacity gain

To improve the overlaid system performance we have considered a TDMA load a_T=25 Erl. Then, from previous results we can conclude that the co-channel ordered slots strategies and the power control scheme on the TDMA system increase the total system capacity in a factor equal to 1.25 This is possible for a CDMA performance P_b<10% and a TDMA performance P_0<16%.

If better conditions of quality are required, the offered load of the TDMA layer can be reduced.

Conclusions

From the results we can observe that in the assumed macrocell scenario, the overlay situation is not possible if only filtering is used. Therefore, in addition to the filtering techniques which are not enough to reduce the impact of the interference between the layers of the overlaid system, two new ideas the ordered hunt and slots reallocation of the TDMA co-channel slots were proposed. Thus, it was theoretically shown that the CDMA overlaying can increase the total system capacity because of the power control in the TDMA layer and the slot allocation strategies.

In this work we have obtained general expressions of the performance of the forward link for different scenarios as a function of the value, which is the limiting factor on the overlaid capacity. In fact, with smaller ratios, higher capacities of the overlaid system can be achieved. Without power control on the TDMA layer the overlaid system has a poor performance. Then, from previous results we can conclude that the co-channel ordered slots strategies and the power control scheme on the TDMA system increase the total system capacity in a factor equal to 1.25 This is possible for a CDMA performance P_b<10% and a TDMA performance P_0<16%.

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