Ordered Hunt Schemes for Overlaid CDMA Cellular Systems

Esquemas de ordenamiento en sistemas celulares sobreptuestos 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, orderedhunt.

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
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.

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

**Introducción**

El crecimiento continuo en el tráfico y la emergencia de nuevos servicios están aumentando la tasa de cambio en los sistemas inalámbricos. Para apreciar el crecimiento del sector inalámbrico, notemos que en 1990 sólo existía 10 millones de suscriptores de teléfono celular, mientras que en China, más de 15 millones de suscriptores se están agregando cada mes; más de la cantidad total de suscriptores que existían a principios de los años 90. En el mundo entero, el crecimiento del sector inalámbrico hasta 1991 [1-3]. Con el progreso de la red inalámbrica en telecomunicaciones, el uso eficiente del espacio disponible es crucial. Un paso en esta dirección es el sistema de superposición de espectro, que podría utilizarse como una forma fácil de migración hacia el sistema de tercera generación (por ejemplo, IS-136 a CDMA2000 o GSM a WCDMA).

Un gran número de autores han explorado el desempeño del CDMA superpuesto. Por ejemplo, algunos trabajos han desarrollado la implementación de la superposición de CDMA y sistemas de transmisión de ondas de microondas [5-11]. En otros, el desempeño del CDMA superpuesto con sistemas de multiplexión en frecuencia (FDMA) o sistemas de multiplexión en tiempo (TDMA) ha sido estudiado en términos de modelos analíticos, que cuantifican una ratio SIR determinista para diferentes escenarios [12-18].

Para implementar exitosamente la superposición de sistemas, en un camino tal que ningún grupo de usuarios cause interferencia excesiva al otro grupo, se ha propuesto el uso de filtros de reducción de interferencia en los transmisores y receptores del CDMA.

Un gran número de autores han explorado el desempeño de la superposición de interferencia en los sistemas de CDMA superpuestos [19-39]. Algunos de estos estudios han centrado su atención en la cuantificación de la ratio SIR en el efecto de la interferencia en el espacio del enlace, y otras han obtenido la ratio de bit-errortrate (BER) desempeño.

Como una forma para mejorar el desempeño del CDMA superpuesto, otros autores examinan el uso de técnicas de multicarretera CDMA [40-44]. Otra propuesta alternativa es el uso de espectro-diversidad superposición de frecuencia (FD-SS) [12, 44]. Uno de los últimos propósitos propuestos es el uso de señales de interferencia en los sistemas de CDMA, y otras han obtenido la ratio bit-errortrate (BER) desempeño.

Motivado por el hecho de que la mayoría de los trabajos existentes se han hecho parcialmente a través de medidas, simulaciones y modelos analíticos simplificados; el primer objetivo de nuestro trabajo es establecer un modelo matemático para evaluar el desempeño en términos de la capacidad de Erlang del sistema superpuesto.

Por lo tanto, evaluaremos la capacidad del sistema superpuesto de CDMA y TDMA sistemas considerando la naturaleza de los Poisson del tráfico, la actividad de actividad en el conmutador, imperfecciones en el círculo de control de potencia, intercepción de la célula adyacente, y el uso de filtros de supresión. Nuestro segundo objetivo es demostrar que la interferencia no rechazada por los filtros es bastante perjudicial para el sistema superpuesto. No obstante, hemos propuesto un nuevo mecanismo para reducir el efecto de interferencia, que implica el ordenamiento y realocación de los slots TDMA.
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 macro-cells 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 \((E_s/I_0)\), 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 \((E_s/I_0)_{k(req)}\) 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, \(e_k\) (with parameters of its characteristic Gaussian random variable, mean \(m_k\) and standard deviation \(\sigma_k\)), will model the variable \((E_s/I_0)_k\) of each user. Then, some typical values are, \(\sigma_k=1.5\)dB and \(m_k=(E_s/I_0)_{k(req)}\) [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 \((\lambda/\tau)_{C(k)}=a_{C(k)}\). In previous equation, \(\lambda\) is the arrival rate, and \(\tau\) is the call duration.

c) The activity factor for each \(k\) class of service is modeled as a binary distributed random variable, \(\nu_k\), with \(P(\nu_k=1)=p_k\).

**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

\[
N_{TS} = \frac{B_T n_T}{s K_T B_{TS}}
\]

(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>
<thead>
<tr>
<th>(B_T)</th>
<th>(W_C) bandwidth</th>
<th>Number of (n_{TSC}) slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 MHz</td>
<td>1.2288 MHz</td>
<td>6</td>
</tr>
<tr>
<td>(n_T=3) and (K_T=7)</td>
<td>3.6864 MHz</td>
<td>18</td>
</tr>
<tr>
<td>7.3728 MHz</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>
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 $W_{Toc} = s_K W_T n_T$.

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. This setup corresponds to a situation 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 $W_{Toc,ef}$ 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 $0 \leq q \leq n_{TSC}$, is expressed as

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

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

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where

$$P(N_T=q) = \sum_{k=0}^{a_{TFC} n_{TSC} / k!} \frac{n_{TSC}!}{(j-q)! (n_{TSC} - j + q)!} \frac{n_{TSC}!}{q! (n_{TSC} - q)!} \frac{a_{TFC}!}{j!} \left( \frac{N_{TS}}{j} \right)$$

$$= \left\{ \begin{array}{ll}
\frac{a_{TFC} j^j j!}{k!}
\end{array} \right\}$$

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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

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

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where \( a_T \) is the TDMA load given by the product of the arrival rate, \( \lambda_T \), and the mean service time, \( 1/\tau_T \). 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 \( a_T=25 \) Erl. This value originates a blocking probability of 3.0135e-009.

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

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

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

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

\[
\left( \begin{array}{c} N_{TS} \\ u \end{array} \right) = \frac{N_{TS}!}{u!(N_{TS}-u)!}
\]

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

\[ P(N_T = q) = \left\{ \begin{array}{l}
P(\text{Non of the co-channel}) = P(\text{Non of the co-channel}) = P(\text{Non of the co-channel}) = \\
(\text{slot is busy}) = P(\text{slot is busy}) = P(\text{slot is busy}) = \\
(\text{slots are busy}) = P(\text{slots are busy}) = P(\text{slots are busy}) = \\
= P(0,0,...,0) + ... + P(1,0,...,0) = 0 < q \leq n_{TSC}
\end{array} \right. \]  

(6)

where the mark $\rightarrow$ 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 \[ [53] \]

\[ P(q - th \text{ slot is busy}) = a_T [B(q - 1, a_T) - B(q, a_T)] \]  

(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 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 $E_0, \ldots, E_{N_{TS}}$ of an Erlang loss system.

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

\[ P(N_T = q) = \left\{ \begin{array}{l}
P(\text{Non of the co-channel}) = P(\text{Non of the co-channel}) = P(\text{Non of the co-channel}) = \\
\sum_{r=0}^{N_{TS} - n_{TSC}} B(r, a_T) = 0 < q \leq n_{TSC}
\end{array} \right. \]  

(8)
where $B(q, a_T)$ is the Erlang-B formula, given by

$$B(q, a_T) = \frac{a_T^q}{q!} \sum_{r=0}^{N_{TS}-1} \binom{N_{TS}-1}{r} \frac{a_T^r}{r!}$$

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 increased in comparison with the previous schemes. Additionally, we have that

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

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

Figure 4. Probability density function of $N_T$ for $a_T=48.7\text{Erl}$ and $a_T=25\text{Erl}$, considering ordered hunt and $W_c=1.2288\text{MHz}$

Figure 5. Markov chain model for TDMA system with ordered hunt and reallocation of the slots
Ordered Hunt Schemes for Overlaid CDMA Cellular Systems

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

$$\left(\begin{array}{c}
E_k \\
I_0
\end{array}\right)_i = \left(\frac{W_{Cf}}{R_i}c^0_{i(i)}\right)_i = \frac{W_{Cf}}{I_{C,C}W_{Cf} + I_{C,T}W_{Tef} + N_0W_{Cf}},$$

where $W_{Cf}$ is the effective spreading bandwidth, $R_i$ is the transmission rate of the $i$-th class of service, $c^0_{i(i)}$ is the fraction of the total power received by user 1 of class $i$ from the 0-th base station. $I_{C,C}W_{Cf}$ and $I_{C,T}W_{Tef}$ are the interference power in the CDMA user due to CDMA and TDMA base stations respectively and $N_0W_{Cf}$ is the power of the thermal noise. In (11) we have

$$I_{C,C}W_{Cf} = F_{(1)}\left[\sum_{j=2}^{N_k} c^0_{i(j)} + \sum_{k=1}^{N_k} N_k c^0_{k(i)}\right] + I_{\text{other}(1)}$$

where $F_{(1)}$ represents the impact of the loss of orthogonally at user 1 of class $i$ in the downlink and $F_{(1)}\in[0,1]$. 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, $F_{(1)}=0$ indicates that the orthogonally of the own cell signal is maintained at the receiver, while $0<F_{(1)}<1$ corresponds to the case where the orthogonally is partly or fully destroyed. $N_k$ 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. $I_{\text{other}(1)}$ 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

$$c^0_{i(i)} = \omega_{(1)}\left[\sum_{j=2}^{N_k} c^0_{i(j)} + \sum_{k=1}^{N_k} N_k c^0_{k(i)}\right] = \omega_{(1)}c^0,$$

where $\omega_{(1)}$ 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

$$I_{C,T}W_{Tef} = \sum_{l=2}^{N_k} N_k c^0_{l(i)}$$

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

![Figure 6. Probability density function of $N_T$ for $\alpha_1=48.7Erl$ and $\alpha_2=25Erl$, considering ordered hunt and reallocation of slots and $W_C=1.2288MHz$](image)
$N_{BS} - N_{BS_{0/0}}$ is the number of interfering base stations included in the system.

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

$$\omega_{t(1)} = \left( \frac{E_b}{I_0} \right)_{t(1)} \frac{R_f}{W_{Cf}} \left[ F_{t(1)} + f_{t(1)} + \sum_{i=0}^{N_b} \sum_{j=1}^{N_f} F_{t(j)} \right] 
+ \sum_{i=0}^{N_b} \sum_{j=1}^{N_f} \left( \frac{1}{c_0} \right) \left( 1 - \frac{E_{I_{W_{Cf}}}}{c_0} \right)$$

(15)

where $f_{t(1)}$ 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 $(1-\theta)$. Therefore, the remaining fraction $\theta$ 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]

$$P_{f_{C}} = P \left( \sum_{k=1}^{N_b} \sum_{j=1}^{N_f} \omega_{k(j)} V_{j(k)} > \theta \right)$$

$$= P \left( \sum_{k=1}^{N_b} \sum_{j=1}^{N_f} \left( \frac{E_b}{I_0} \right)_{k(j)} \frac{R_f}{W_{Cf}} \left[ F_{t(j)} + f_{t(j)} \right] + \sum_{i=0}^{N_b} \sum_{j=1}^{N_f} \left( \frac{1}{c_0} \right) \left( 1 - \frac{E_{I_{W_{Cf}}}}{c_0} \right) \right) > \theta = P(Z > \theta),$$

(16)

where $V_j$ is the activity of the users of the $k$-th service class modeled as a binary random variable and $(E_b/I_0)_{k(j)}$ 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 $f_{t(j)}$ 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

$$P_{f_{C}} = Q \left( \frac{\theta - E\{Z\}}{\sqrt{Var\{Z\}}} \right)$$

(17)

where $\theta$ 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

$$E\{Z\} = \sum_{k=1}^{N_b} \sum_{j=1}^{N_f} \omega_{k(j)} V_{j(k)} \frac{R_f}{W_{Cf}}$$

$$Var\{Z\} = \sum_{k=1}^{N_b} \sum_{j=1}^{N_f} \omega_{k(j)} V_{j(k)} \frac{R_f}{W_{Cf}}$$

$$\exp \left( \left( \beta \sigma_z \right)^2 / 2 \right) \exp \left( \beta m_z \right)$$

$$\exp \left( 2 \left( \beta \sigma_z \right)^2 \right) \exp \left( 2 \beta m_z \right)$$

(18)

where $a_{C(k)}(1+2g)$ is the traffic load of the CDMA system, $\rho_k$ is the activity factor of the $k$-th class of service, $\beta=\ln(10)/10, \sigma_z=1.5$ dB, $m_k=(E_b/I_0)_{k(req)}$, $f_{t(j)}^{forward}$ 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 $(1-2p/1-p)$. $F$ 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 $E\{I_{C(j)}W_{Tas,ef}/c_0\}$ and $E\{(I_{C(j)}W_{Tas,ef}/c_0)^2\}$ are obtained assuming two different scenarios; the TDMA system without power control and with power control.
We have that the received power on the interest CDMA user from the \( l \)-th BS is

\[
(T_{\langle i \rangle})_{\text{NPC}} = \frac{P_{T(i)}}{(r_{l}^{i})^{\mu}} 10^{\frac{y_{l} - y}{10}} \quad \text{and}
\]

\[
(T_{\langle i \rangle})_{\text{PC}} = \frac{P_{T(i)}}{(r_{l}^{i})^{\mu}} 10^{\frac{y_{l} - y}{10}},
\]

(19)

where \( P_{T} \) is the transmitted power by the TDMA base station per user, and \((r_{l}^{i})^{\mu} 10^{\frac{y_{l} - y}{10}}\) models the propagation losses given by the product of the \( \mu \)-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 \( \zeta_{0} \) is the dB attenuation with zero mean and standard deviation \( \Delta \). \( P_{T(i)}^{l} \) 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

\[
P_{T(i)}^{l} = e^{\frac{\beta_{l}^2}{2}} \int_{B_{S_{j}}} P_{T} (r_{l}^{i})^{\mu} f(a) da
\]

(20)

where \((r_{l}^{i})^{\mu}\) is the distance between the \( l \)-th base station and all the possible positions of the \( j \)-th TDMA user inside the coverage area of the \( l \)-th BS and \( f(a) = 1/\text{cell area} \).

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

\[
E\left[ \frac{I_{C,T} W_{\text{Max,cf}}}{c_{0}} \right] = E\{ Y \} = \exp\left( (\beta S\{ y \})^2 / 2 \right) \exp(\beta E(y))
\]

(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

\[
p_{\text{forward}}(x, y) = \frac{1}{\text{Max}} \sum_{i=j}^{\text{Max}} p_{\text{forward}}(x, y),
\]

(22)

where \( \text{Max} \) 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, \( SIR_{T\text{(req)}} \), known as the outage probability. Hence, the outage probability due to the \( q \)-th slot is busy, is given by

\[
P_{\text{outage}}(q) = P\left( \frac{SIR_{T} < SIR_{T\text{(req)}}}{q \text{-th slot is busy}} \right)
\]

\[
P(q \text{-th slot is busy})
\]

(23)

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

\[
P\left( \frac{SIR_{T} < SIR_{T\text{(req)}}}{q \text{-th slot is busy}} \right) = P\left( \frac{T_{D}}{I_{T,T} W_{T} + I_{T,C} W_{\text{Max}}} < SIR_{T\text{(req)}} \right)
\]

(24)

where \( T_{D} \) is the power of the desired signal on the TDMA system, \( I_{T,T} W_{T} \) and \( I_{T,C} W_{\text{Max}} \) are the powers of the interference in the TDMA system due to TDMA and CDMA systems respectively.

In (24)

\[
I_{T,C} W_{\text{Max}} = W_{T} \sum_{k=1}^{N_{k}} \sum_{i=1}^{N_{i}} \sum_{j=1}^{N_{j}} v_{k(i)}^{j} e_{k(j)}^{i} R_{k}(I_{0})_{k}
\]

(25)

where \( N_{k} \) is a Poisson random variable which models the CDMA active users, \( v_{k(i)}^{j} \) and \( e_{k(j)}^{i} \) are a binary and log-normal random variables which defines the activity of the services and the \( (E_{k}/I_{0})_{k} \) 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 \( W_{\text{Max}} \) is the effective spreading bandwidth. Again, the evaluation of (24) is conditioned to the consideration or not of power control in the TDMA layer.
TDMA System without and with power control

Without power control

\[
\begin{align*}
T_D \left( I_{T,T} W_T + I_{T,C} W_{Cf} \right)_{NPC} & = P_r \\
= \sum_{j=0}^{N_{R}} \sum_{l=1}^{2} \frac{k^{1/2}}{r_{0(j)}} 10^{k r_{0(j)} / \alpha} \frac{W_r}{W_{Cf}} \sum_{k=1}^{N_z} \sum_{k=1}^{2} \nu_{k(j)} v_{k(j)} R_k (l_k) \sum_{k=1}^{N_z} \sum_{k=1}^{2} \nu_{k(j)} v_{k(j)} \alpha_{NPC_k} \sum_{k=1}^{N_z} \sum_{k=1}^{2} \nu_{k(j)} v_{k(j)} \alpha_{NPC_k} \\
& = \frac{X_{NPC}}{Z_{NPC} + Y_{NPC}} \quad (26)
\end{align*}
\]

where \( \alpha_{NPC_k} \) 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

\[
E(x_{NPC}) = 101 \log_{10} \left( \frac{1}{r_{0(j)}} \right) \quad \text{and} \quad S(x_{NPC}) = \Delta \quad (27)
\]

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

\[
P \left( \frac{X_{NPC}}{Z_{NPC} + Y_{NPC}} < \text{SIR}_{T(\nu_0)} \right) = \int_{-\infty}^{\text{SIR}_{T(\nu_0)}} \frac{e^{-u^2/2}}{\sqrt{2\pi}} du \quad (28)
\]

\[
\int_{-\infty}^{\text{SIR}_{T(\nu_0)}} \frac{e^{-u^2/2}}{\sqrt{2\pi}} du \quad (29)
\]

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

\[
E(Y_{NPC}) = \int_{0}^{\infty} \frac{W_r}{W_{Cf}} \sum_{k=1}^{N_z} \sum_{k=1}^{2} \nu_{k(j)} v_{k(j)} (1+2g) \cdot \exp \left( \frac{\beta \sigma_y^2}{2} \right) \exp (\beta m_z) \cdot \exp \left( \frac{\beta \sigma_y^2}{2} \right) \exp (\beta m_z) \quad (29)
\]

where \( \alpha_{NPC_k} \) 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

\[
P \left( \frac{1}{Z_{PC} + Y_{NPC}} < \text{SIR}_{T(\nu_0)} \right) = \int_{-\infty}^{\text{SIR}_{T(\nu_0)}} \frac{e^{-u^2/2}}{\sqrt{2\pi}} du \quad (30)
\]

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

\[
E(Y_{PC}) = \int_{0}^{\infty} \frac{W_r}{W_{Cf}} \sum_{k=1}^{N_z} \sum_{k=1}^{2} \nu_{k(j)} v_{k(j)} (1+2g) \cdot \exp \left( \frac{\beta \sigma_y^2}{2} \right) \exp (\beta m_z) \cdot \exp \left( \frac{\beta \sigma_y^2}{2} \right) \exp (\beta m_z) \quad (29)
\]

\[
Var(Y_{PC}) = \int_{0}^{\infty} \frac{W_r}{W_{Cf}} \sum_{k=1}^{N_z} \sum_{k=1}^{2} \nu_{k(j)} v_{k(j)} (1+2g) \cdot \exp \left( \frac{\beta \sigma_y^2}{2} \right) \exp (\beta m_z) \cdot \exp \left( \frac{\beta \sigma_y^2}{2} \right) \exp (\beta m_z) \quad (29)
\]

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\[ p_k R^2 a_{(PC)^k} \exp(2\beta \sigma_k) \exp(2\beta m_k), \]  
\( (31) \)

where \( a_{(PC)^k} \) 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

\[ P_{\text{down}}^{\text{down}}(\chi_i,\gamma_i) = \frac{1}{N_{\text{pos}}} \sum_{i=1}^{N_{\text{pos}}} p_{\text{down}}^{\text{down}}(\chi_i,\gamma_i) \]

\( (32) \)

where \( N_{\text{pos}} \) 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 \( \gamma \) and \( \alpha \), the service time on the TDMA layer equal to 2 minutes, \( \Delta=8\text{ dB}, \mu=4, f_{C_{\text{forward}}}=0.5632 \) (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 without 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, \( a_{(\text{voice})}=16.44 \text{ Erl} \) and \( a_{(\text{data})}=1 \text{ Erl} \) for a blocking probability of around 2%. The TDMA system has been evaluated when it operates at a tolerable capacity, \( a_{T}=25 \text{ Erl} \) for a blocking probability less than 2%.

Table 3 shows the CDMA and TDMA power requirements for different values of the \( \gamma \) and \( \alpha \) ratios. As we mentioned previously \( \gamma \) and \( \alpha \) 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, \( \gamma_{NPC} \) 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 \( a_{(NPC)^k} \) 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, \( \gamma_{PC} \) 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 \( a_{(PC)^k} \) 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)**

<table>
<thead>
<tr>
<th></th>
<th>CDMA</th>
<th>TDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel spacing</td>
<td>( W_C =1.2288 \text{MHz} )</td>
<td>( W_T =10 \text{ kHz} )</td>
</tr>
<tr>
<td>Time slot structure</td>
<td>N/A</td>
<td>( N_{\text{TS}}=59 )</td>
</tr>
<tr>
<td>Co-channel time slots</td>
<td>N/A</td>
<td>1.2288 MHz/( f_{\text{TSC}}=6 )</td>
</tr>
<tr>
<td>Voice Service</td>
<td>( (E_b/I_0)_{\text{(req)}}=5.4 \text{ dB} )</td>
<td>( SIR_{\text{(req)}}=17 \text{ dB} )</td>
</tr>
<tr>
<td>Data Services</td>
<td>LCD 64k</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>( (E_b/I_0)_{\text{(req)}}=3.8 \text{ dB} )</td>
<td>( R=64 \text{ Kbps} )</td>
</tr>
<tr>
<td></td>
<td>( \rho=1 )</td>
<td>( R=8 \text{ Kbps} )</td>
</tr>
<tr>
<td>Power control</td>
<td>Yes</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Cell Size</td>
<td>1km</td>
<td>1Km</td>
</tr>
</tbody>
</table>

**DOI:** http://dx.doi.org/10.22201/fi.25940732e.2010.11n3.030
In Table 3 as a way to approximate the parameter $\alpha$, we assume that the maximum tolerable CDMA spectral interference density is given by

$$I_{\text{max}} = \frac{P_{\text{CDMA}}}{{R_k}^4} \cdot \frac{{E_b}}{{I_{\text{g}}}}.$$  

Where $R_k$ and $E_b$ 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 $d_T = 25$Erl, 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 $\alpha$, 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.

<table>
<thead>
<tr>
<th>$P_{\text{TDMA}},(\text{BS})$</th>
<th>$P_{\text{TDMA}},(\text{Mobile})$</th>
<th>$P_{\text{CDMA}},(\text{BS})$</th>
<th>$P_{\text{CDMA}},(\text{Mobile})$</th>
<th>$P_{\text{TDMAtx}},(\text{BS})$</th>
<th>$P_{\text{TDMAtx}},(\text{Mobile})$</th>
<th>$P_{\text{CDMAtx}},(\text{BS})$</th>
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<td>17.04W</td>
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<td>6.67E-18</td>
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<td>9.54E-17</td>
<td>3.2E-5</td>
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<td>1.33E-17</td>
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<td>1.33E-5</td>
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<td>0.2083</td>
<td>9.54E-17</td>
<td>3.2E-17</td>
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<td>3.2E-5</td>
<td>9.54E-17</td>
<td>3.2E-5</td>
</tr>
</tbody>
</table>
Ordered Hunt Schemes for Overlaid CDMA Cellular Systems

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

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

Figure 9. Forward link CDMA performance for a partial TDMA load $a_T = 25\text{Erl}$ 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 $\gamma$ value, which is the limiting factor on the overlaid capacity. In fact, with smaller $\gamma$ ratios, higher capacities of the overlay 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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