Multicell S-ALOHA DS-CDMA networks with Fast Power Control Error under Frequency-selective Nakagami Fading

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Abstract

In this paper, we have investigated the performance of a multicell S-ALOHA DS-CDMA system with fast power control error on a Nakagami frequency selective environment. We analyzed how the throughput of the optimally stabilized system is affected by the channel conditions and some key system characteristics such as the processing gain or the number of fingers in the RAKE receiver. By using an ideal retransmission probability that takes into account not only the number of users in backlog but also the DS-CDMA channel conditions we obtain the maximal achievable throughput of a S-ALOHA DS-CDMA system for a given DS-CDMA channel. These curves can be used as an upperbound for currently used S-ALOHA DS-CDMA systems. The results obtained reflect that, if fast power control is used, the system throughput is very robust against varying channel conditions provided that the processing gain and the EbN0 are above some threshold values.

Keywords

Slotted ALOHA, DS-CDMA, fast Power Control Error, Nakagami Fading, BER
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Abstract— In this paper, we have investigated the performance of a multicell S-ALOHA DS-CDMA system with fast power control error on a Nakagami frequency selective environment. We analyzed how the throughput of the optimally stabilized system is affected by the channel conditions and some key system characteristics such as the processing gain or the number of fingers in the RAKE receiver. By using an ideal retransmission probability that takes into account not only the number of users in backlog but also the DS-CDMA channel conditions we obtain the maximal achievable throughput of a S-ALOHA DS-CDMA system for a given DS-CDMA channel. These curves can be used as an upperbound for currently used S-ALOHA DS-CDMA systems. The results obtained reflect that, if fast power control is used, the system throughput is very robust against varying channel conditions provided that the processing gain and the $\frac{E_b}{N_0}$ are above some threshold values.

Index Terms— Slotted ALOHA, DS-CDMA, fast Power Control Error, Nakagami Fading, BER

I. INTRODUCTION

Slotted ALOHA (S-ALOHA) DS-CDMA schemes are currently used for random access channels and bursty data channels because they offer the possibility to combine the properties of both DS-CDMA (i.e. the statistical multiplexing), and slotted ALOHA (i.e. simplicity and random access) to achieve higher spectrum utilization [1]. Due to the inherent instability of the ALOHA schemes the S-ALOHA DS-CDMA networks use different techniques to stabilize the system and allow its correct operation.

In spite of the vast literature on S-ALOHA protocols and its variants, the combination of S-ALOHA and DS-CDMA has received less attention and, as far as we know, there are still some important issues that have not been fully assessed as yet. In [2], [3] provided a realistic framework for evaluating S-ALOHA DS-CDMA schemes but the analysis was constrained to a single cell system over an AWGN channel and did not consider a stabilized system. A stability analysis of a S-ALOHA spread spectrum system was performed in [4] but the DS-CDMA component was not accurately modelled. In [5] a multicell system over a Nakagami fading channel was analyzed, although again the stabilized system operation was not considered and the performance of the system in terms of throughput was not studied. Our paper differs from the previous literature in that it performs a precise modelling of the DS-CDMA physical layer and the wideband channel that contrary to existent studies (p.e.[6], [7], [8]) allows the derivation of an accurate closed form expression for the average bit error rate (BER) by taking into account fast power control imperfections and frequency selective Nakagami fading. We are interested then on the performance of a stabilized S-ALOHA DS-CDMA multicellular network and how this performance is affected by the DS-CDMA physical layer and channel.

Extending the method in [3], in this paper we will use the same S-ALOHA DS-CDMA system model that we already used in [9] and [10] but in this case we will investigate the behavior of a fast power controlled system instead of the slow power control scheme proposed in [10]. This analytical model will allow us to obtain the expressions of the ideal retransmission probability that stabilize the system in an optimal way, the throughput figures obtained in this ideal system are an upperbound for any of the currently used non ideal stabilization methods.

The paper is organized as follows. A general system model description is provided in sect.II. In sect.III we describe the maximal system throughput calculation, determine the packet error rate and describe its dependency on the channel bit error rate. In sect. IV we obtain the BER expression and in sect.V we analyze the system performance. Conclusions are summarized in sect. VI.

II. SYSTEM MODEL DESCRIPTION

In a S-ALOHA DS-CDMA network a set of spreading codes is assigned to each Base Station (BS) that broadcast the identities of these codes to all its Mobile Stations (MS). Moreover, time is slotted into segments in all BSs of the network. The slot duration is equal to the transmission time of a packet just as in a conventional slotted ALOHA system. Whenever a MS has a packet to send to its BS, it spreads the packet by randomly choosing one of the spreading codes and transmits the packet in the next time slot. If several MSs transmit packets in the same time slot the transmission will be successful if:
first, the MSs use different spreading codes and the receivers at the BS are able to distinguish the packets and thus to acquire them and,

second, packets correctly acquired are received successfully, that is without bit errors after applying error correction codes (the reception may or may not be successful due to the random interference from the multiple transmissions performed by MSs of the same and adjacent cells inherent to DS-CDMA).

Non successful packets will have to be retransmitted in some latter time slot.

The system model is shown in Fig.1 and its parameters are described in Table 1. We consider a two dimensional layout of hexagonal cells with a BS located at the center of every cell. We use a system model of \(N_{BS0}\) unbuffered MSs in the central cell (BS0) or cell-of-interest. At the beginning of a time slot each MS is assumed to be in one of two modes: I-mode (Idle, without a packet ready for transmission) or B-mode (Backlogged, with a ready for transmission packet). A MS that either 1) just joins the system or 2) has had a successful packet transmission is said to be in I-mode. It is assumed that a MS in I-mode will generate a packet in the next time slot and pass to B-mode with probability \(P_{I\rightarrow B}\). On the other hand, the MSs in B-mode are those who have packets waiting for transmission because: 1) were in I-mode and generated a packet or 2) have had an unsuccessful packet transmission and wait for a retransmission. It is assumed that a MS in B-mode will transmit a packet in the next time slot with a probability \(P_{B0}\). It is also assumed that a MS in B-mode will not generate new packets. It is said that a MS in B-mode that transmits/retransmits a packet has acquired one of the \(K_0\) system codes if no other B-mode MS with an ongoing transmission in the current time slot selected the same code. The transmissions of this cell will be affected by a certain Packet Success Rate (\(P_{CS}\)) depending on the channel characteristics and the existing interference level. For \(N_{0,k}^{(T)}\) simultaneous transmissions in cell \(q = 0\) and slot \(k\) there are \(N_{0,k}^{(T)} - 1\) intracell interferers and \(M_0T\) intercell interferers. Assuming that the cells are synchronized at the slot level \(M_0T\) is the sum of the mobiles transmitting in the same interval but not connected to the BS0. The radio channel used to calculate \(P_{Cq}\) is affected by long and short term fluctuations. Long term variations are due to distance loss with path loss exponent \(\mu\) and shadowing, which is modelled as a log-normal random variable \(10^{\xi/10}\) where \(\xi\) is assumed to follow a zero-mean Gaussian distribution with variance \(\sigma_{\xi h}\). We assume also that multipath propagation results in the reception of \(L\) paths with Nakagami distribution, and RAKE receivers of \(L\) fingers are assumed to optimally combine the individual paths. Every BS transmits a pilot signal and mobile stations (MS) connect to the BS whose pilot is received with the highest average power level. As a given MS may not be able to measure the pilot signals of all the BSs in the system, the selection will be considered as limited to the \(Q_C\) nearest BSs. This limitation can also be justified by the use of neighbor cell lists by the MSs, where MSs are regularly provided with a list of handover candidates to be monitored [7][11]. We denote as \(S_0\), with area \(A_0\), the region of the plane containing all the points having the central base station (BS0) included among the \(Q_C\) nearest BSs, and as \(S_1\), with area \(A_1\), the region containing all the points not having BS0 within the \(Q_C\) nearest BSs. The size and shape of these regions are a function of \(Q_C\), and examples can be found in [7][11]. Moreover, it is assumed that the system is fast power controlled thanks to a slow signalling channel between any MS and its BS. Power control error (PCE) will exist and for any user \(i\) will be modelled as a log-normal random variable.

### III. System Analysis

Let us assume that the cell-of-interest (\(q = 0\)) is at state \(B\) (i.e. the number of MSs in backlog \(N_{0,k}^{(B)} = B\)). Now let \(S_{0}^{in}(B)\) and \(S_{0}^{out}(B)\) be, respectively, the mean number of net packet flows into the BS0 system (the mean \(N_{0,k}^{(N)}\)) and the mean number of packet flows out of the system (the mean \(N_{0,k}^{(S)}\) in a time slot. If \(S_{0}^{in}(B) > S_{0}^{out}(B)\) or \(S_{0}^{in}(B) < S_{0}^{out}(B)\), then the system tends to drift to a higher (> B) or to a lower (< B) state, respectively. If \(S_{0}^{in}(B) = S_{0}^{out}(B)\), then \(B\) is an equilibrium state. An equilibrium state can be either stable or unstable. If the number of equilibrium states is one, the system is said to be stable. Otherwise it is said to be

<table>
<thead>
<tr>
<th>Par</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>(Q)</td>
<td>Number of cells in the network</td>
</tr>
<tr>
<td>(N_{q})</td>
<td>Number of MSs in cell (q)</td>
</tr>
<tr>
<td>(K)</td>
<td>Number of receiver-code pairs in cell (q)</td>
</tr>
<tr>
<td>(N_{q}^{(B)})</td>
<td>Num. MSs in B-mode beginning slot (k) cell (q)</td>
</tr>
<tr>
<td>(N_{q}^{(I)})</td>
<td>Num. MSs in I-mode beginning slot (k) cell (q)</td>
</tr>
<tr>
<td>(N_{q}^{(T)})</td>
<td>Total MSs number transmitting packets slot (k) cell (q)</td>
</tr>
<tr>
<td>(N_{q}^{(N)})</td>
<td>Num. MSs in I-mode generating packet slot (k) cell (q)</td>
</tr>
<tr>
<td>(N_{q}^{(A)})</td>
<td>Num. packets acquired slot (k) cell (q)</td>
</tr>
<tr>
<td>(N_{q}^{(S)})</td>
<td>Num. packets correctly received slot (k) cell (q)</td>
</tr>
<tr>
<td>(P_{Dq})</td>
<td>Prob. a MS in I-mode generates packet in a slot cell (q)</td>
</tr>
<tr>
<td>(P_{Bq})</td>
<td>Prob. a MS in B-mode transmission packet in a slot cell (q)</td>
</tr>
<tr>
<td>(M_{qT})</td>
<td>Num. intercell interferers present in slot (k) cell (q)</td>
</tr>
<tr>
<td>(P_{Cq})</td>
<td>Average packet success probability in cell (q)</td>
</tr>
</tbody>
</table>
unstable. Notice that when the system reaches an equilibrium state $B_e$ the mean system throughput coincides with $S_{0\text{out}}^e(B_e)$.

The mean number of packet flows out of the BS0 system $S_{0\text{out}}^e(B)$ is [9]

$$ S_{0\text{out}}^e(B) = \sum_{n=0}^{B} \left( \sum_{s=0}^{\text{min}(K_0,n)} s \left( \frac{B}{n} \right) \right) \sum_{i=0}^{n} \binom{n}{i} \left( 1 - P_{R_0}^{-1}(1 - P_{R_0}) \right)^{(B-n)} \times P_r\{N_{0,k}^{(S)} = s | N_{0,k}^{(T)} = n\}, \tag{1} $$

where

$$ P_r\{N_{0,k}^{(S)} = s | N_{0,k}^{(T)} = n\} = \sum_{a=0}^{\text{min}(K_0,n)} \left( \frac{a}{s} \right) P_C(n)^s [1 - P_C(n)]^{a-s} \times \sum_{n=0}^{\text{min}(K_n,0)} \binom{K_0}{a} \binom{a}{s} \alpha T_{n-a,K_0-a} \frac{K_0^n}{K_0^{a}}, \tag{2} $$

if $0 \leq s \leq a$ and 0 otherwise, where $P_C(n)$ is the packet success rate for $n$ simultaneous transmissions in the cell-of-interest ($N_{0}^{(T)} = n$) and

$$ T_{x,y} = y^T - \left[ \sum_{i=1}^{n} \binom{x}{y} \left( \begin{array}{c} x \\ i \\ \end{array} \right) \right]. \tag{3} $$

Deriving (1) with respect to $P_{R_0}$ in [9] we obtain

$$ \frac{\partial S_{0\text{out}}^e(B)}{\partial P_{R_0}} = \sum_{n=0}^{N_{R_0}} \left( \sum_{s=0}^{\text{min}(K_0,n)} s \left( \frac{B}{n} \right) \right) \sum_{i=0}^{n} \binom{n}{i} \left( 1 - P_{R_0}^{-1}(1 - P_{R_0}) \right)^{(B-n)} \times P_r\{N_{0,k}^{(S)} = s | N_{0,k}^{(T)} = n\}, \tag{4} $$

now finding out the zeros of the derived expression we obtain an adaptive $P_{R_0}$ that ensures stability and at the same time maximizes the throughput of BS0.

To investigate the system performance we should use $P_{R_0}$ to stabilize the system in the cell-of-interest and determine the resulting system throughput using (1). However, the throughput determination requires the calculation of the packet success rate for all possible simultaneous transmissions in the cell-of-interest, that is $P_C(n)$ with $n \in \{1, 2, ..., N_{R_0}\}$. The determination of $P_C(n)$ will imply the calculation of the average bit error rate $P_b(n)$ for all possible values of $n$. Then, if we assume that the anti-fading property of DS-CDMA and the possible interleaving will cause the errors to be independent and identically distributed within a packet and that in addition to a CRC detector code a $t$ error correcting block code is used, then the packet success probability $P_C(n)$ for packets containing $E$ bits can be upperbounded by [2]

$$ P_C(n) \leq \sum_{i=0}^{t} \binom{E}{i} P_b(n)^i (1 - P_b(n))^{E-i}. \tag{5} $$

IV. ERROR PROBABILITY ANALYSIS

A. Transmitter-Receiver and channel model

We use a frequency selective fading channel with impulse response

$$ h_{q_0,k}(\tau, t) = \sqrt{G_c} \sum_{l=0}^{L_{q_0,k}-1} \alpha_{q_0,k,l}(t)e^{j\psi_{q_0,k,l}(t)}(\tau - lT_c) \times d_{k0}^{\mu/2}(x, y)10^{lo/20} \tag{6} $$

where $\mu$ is the power distance loss index, $\xi_{k,0} \sim N(0, \sigma^2_{sh,k,0})$ corresponds to the lognormal shadowing, $L_{q_0,k} = \frac{f_s}{\Delta f} C_{d0,k}$ denotes the number of resolvable paths, $f_s = 1/T_c$ is the bandwidth of the transmitted real bandpass signal, and $(\Delta f) C_{d0,k}$ is the channel coherence bandwidth. If we also assume that the symbol duration is much smaller than the channel coherence time, then $\alpha_{q_0,k,l}(t)e^{j\psi_{q_0,k,l}(t)} = \alpha_{q_0,k,l}e^{j\psi_{q_0,k,l}}$, where the $\{\psi_{q_0,k,l}\}$ are independent random variables uniformly distributed over $[0, 2\pi)$ and $\{\alpha_{q_0,k,l}\}$ are independent Nakagami [12] random variables with parameters, $\Omega_{q_0,k,l} = E(\alpha_{q_0,k,l}^2)$ and $\Omega^2_{q_0,k,l} = \Omega^2_{d0,k,l}/E(\alpha_{q_0,k,l} - \Omega_{q_0,k,l})^2$. $m_{q_0,k,l}$ is the fading parameter of path $l$ between MS $k$ of cell q and BS0 and $\Omega_{q_0,k,l}$ are related to the MIP (contrary to what is used in [7], [8] we will not impose any restriction over the MIP form).

The transmitted low-pass equivalent signal of MS $k$ in cell q (reverse link) is given by

$$ s_k(t) = \sqrt{\frac{2S\lambda_k}{G_c\Phi_{kq}}} d_{k,q}^{\mu/2}(x, y)10^{lo/20} D_k(t - \tau_k)c_k(t - \tau_k)e^{j\theta_k} \tag{7} $$

where $G_c$ is a constant, $S$ represents the received signal amplitude in the absence of fading, $D_k(t)$ is the encoded data waveform of the $k$ user, $c_k(t)$ is the corresponding code sequence waveform, $\tau_k$ indicates each MS has an independent symbol timing due to asynchronous transmission, $\lambda_k$ models the power control error (PCE) amplitude, which is assumed to follow a lognormal distribution [6], [13], [14], [15], [16], and thus, it can be written as $\lambda_k = 10^{x_k/10}$ where $x_k$ is a zero-mean Gaussian random variable with standard deviation $\sigma_{x_k}$, $\phi_k = \theta_k - \omega_c \tau_k$, where $\theta_k$ is the carrier phase and $\omega_c$ is the carrier frequency. Finally the term $\{d_{k,q}^{\mu/2}(x, y)10^{lo/20}\}$ correspond to the distance loss and shadowing power compensation and the term $\Phi_{kq} = \sum_{l=0}^{L_{q_0,k}-1} \alpha_{q_0,k,l}^2$ corresponds to the fast fading compensation performed by the MS $k$ power control to compensate channel attenuations towards its own BS (defined as $\hat{q}$).

To reach the BS of the cell-of-interest (q=0), the above signal will be affected by the channel described above and then the baseband received signal in cell q = 0 can be expressed as

$$ \tilde{r}(t) = \sum_{\forall k} \sqrt{2S\lambda_k} Y_k(x, y) \frac{1}{\Phi_{kq}} d_{k,q}^{\mu/2} \sum_{l=0}^{L_{q_0,k}-1} \alpha_{q_0,k,l}e^{j\psi_{q_0,k,l}} \times D_k(t - \tau_c - \tau_k)c_k(t - \tau_c - \tau_k) + \tilde{n}(t), \tag{8} $$

where $\tilde{n}(t)$ is a complex zero-mean AWGN with single-sided power spectral density $\eta_0$ and
where $\mathcal{S}_{BS0}$ represents MSs located in $S_0$ and connected to BS0 and $\mathcal{S}_{BS0}$ represents MSs located in $S_0$ not connected to BS0.

Assuming a perfect channel estimation process the output of the correlation receiver of the desired MS ($q = 0, k = 1$) can be expressed without loss of generality at a certain $T_b$ as

$$r(T_b) = \text{Re} \left\{ \sum_{l=0}^{L_{q0,1}-1} \alpha_{00,1l} e^{j(\psi_{00,1l} + \phi_l)} \right\} \times \int_{T_c - \tau_l}^{T_c + \tau_l} \bar{r}(t)c_1(t - IT_c - \tau_l)dt \right\}$$

Expression can be decomposed in the following terms

$$r(T_b) = r_u(T_b) + r_{mp}(T_b) + r_{ma}(T_b) + \sum_{n=1}^{Q} r_{mc}(T_b) + \sum_{n=1}^{Q} r_{th}(T_b)$$

where $r_u(T_b) = \sqrt{2SNR}T_b$ is the desired signal component to be detected, $r_{mp}(T_b)$ represents the self interference, $r_{ma}(T_b)$ and $r_{mc}(T_b)$ are the multiple access interference of other MSs in the same cell and surrounding cells respectively, and finally $r_{th}(T_b)$ is the Gaussian random variable due to the AWGN process (Re $r_{th}(T_b)$) = $N(0, T_b \sigma_\text{no}^2 (\sum_{l=0}^{L_{q0,1}-1} \alpha_{00,1l}^2))$. As $(n - 1) + \sum_{n=1}^{Q} M_q >> 1$, $r_{mp}(T_b)$ is much smaller than $r_{ma}(T_b)$ and $r_{mc}(T_b)$, it will be ignored in what follows.

**B. Gaussian Assumption**

Defining $r_{in}(T_b) = r_{mp}(T_b) + r_{ma}(T_b)$ and taking into account that each MS has independent fading, independent PCE and independent geometric location, then $r_{in}(T_b)$ is a sum of independent random variables that applying the Central Limit Theorem we will assume that is Gaussian distributed. The use of the Gaussian assumption in BER calculations is very common [17],[8], since it is found to be quite accurate. Therefore $r_{in}(T)$ is asymptotically Gaussian conditioned on the PCE of the MS-of-interest. Assuming long spreading sequences, a normalized MIP ($\sum_{n=0}^{L_{q0,k}-1} E\{\alpha_{q0,0,k}^2\} = 1$) for all the users, assuming also that $E\left\{\frac{1}{\psi_{q0}}\right\} = E\left\{\frac{1}{\phi}\right\}$ and $E\{\lambda_k\} = e^{\frac{1}{2}B^2\sigma^2}$, where $B \equiv \ln 10^{10}$, the conditional variance of the zero mean Gaussian variable $r_{in}(T)$ is

$$\text{Var}(r_{in}(T)) = \frac{4GP^2T_c^2S}{3} e^{\frac{1}{2}B^2\sigma^2} E\left\{\frac{1}{\Phi}\right\} \times \sum_{l=0}^{L_{q0,1}-1} \alpha_{00,1l}^2 ((n - 1) + \varpi_{SBS0} M_{BS0} + \varpi_{S1} M_{S1})$$

where $G_P$ is the processing gain, $n = N_0^{(T_k)}$, $M_{BS0}$ is the number of users located in $S_0$ that are not connected to BS0, $M_{S1}$ is the number of users located in $S_1$ and $\varpi_{Sx} \equiv E\{\varpi_{Sx}\}$ in $\mathcal{S}_{Sx}$.\text{ denotes the average interference produced by a user located in $\mathcal{S}_x$}

$$\varpi_{Sx} = \left\{ \frac{1}{\lambda_0} \int_{\mathcal{S}_0} E\left\{ e^{-\xi_{S0}^{(k)}} | \gamma_{S0}^{(k)} < 0 \right\} dA_0 \right\} \mathcal{S}_{BS0} = \left\{ \frac{1}{\lambda_1} \int_{\mathcal{S}_1} E\left\{ e^{-\xi_{S1}^{(k)}} \right\} dA_1 \right\} \mathcal{S}_{S1}$$

where

$$\xi_{S0}^{(k)} = -B\xi_{k0} + \min_{q \neq q_0} \left\{ \mu \ln \frac{d_{kq}}{d_{k0}} + B\xi_{kq} \right\}$$

$$\xi_{S1}^{(k)} = -B\xi_{k0} + \min_{q \neq q_0} \left\{ \mu \ln \frac{d_{kq}}{d_{k0}} + B\xi_{kq} \right\}$$

The SNIR at the output of the receiver can be written as $\gamma_{b} = \Psi_n \lambda_1$, where $\Psi_n$ is a constant given by

$$\Psi_n = \frac{e^{\frac{1}{2}B^2\sigma^2}}{\sigma_{\text{no}}} \left( n + \varpi_{SBS0} M_{BS0} + \varpi_{S1} M_{S1} \right) + \frac{N_0}{10}$$

where $E_b = 2ST_bE\left\{\frac{1}{\phi}\right\}$ is the average received bit energy. The random variable $\Phi$ is a sum of gamma variables we can use the Moschopoulos Theorem [18] to find out its PDF

$$p_\Phi(\zeta) = \sum_{k=0}^{\infty} \frac{\beta_k^m}{\Gamma(S_k) \beta_k^n} \delta_k e^{-\zeta/\beta_k} S_k^{-1}$$

where $\beta_n = \Omega_{q0,kn} / \alpha_{q0,kn}$, $\beta_1 = \min_n\{\beta_n\}$, $S_k = \sum_{n=1}^{Q} m_n + k$ and the coefficients $\delta_k$ can be obtained recursively by the formula

$$\begin{cases} \delta_0 = 1 \\ \delta_{k+1} = \frac{1}{k+1} \sum_{i=1}^{k+1} \left[ \sum_{j=1}^{N} m_j (1 - \frac{\beta_j}{\beta_i})^i \right] \end{cases}$$

Moschopoulos [18] provides a rigorous proof for the uniform convergence of (17) and a bound on the truncation error. Using (17) we obtain

$$E\left\{\frac{1}{\Phi}\right\} = \int_{0}^{\infty} p_\Phi(\zeta) d\Phi = \sum_{k=0}^{\infty} \delta_k \beta_k^{-1} \prod_{n=1}^{L_{q0,k}-1} \left( \frac{\beta_k}{\beta_n} \right) m_n \Gamma(S_k^{-1}) \Gamma(S_k)$$

**C. BER calculation**

It is well known [19] that for coherent BPSK modulation in the presence of AWGN, the probability of error conditioned on the instantaneous SNIR can be expressed as

$$P_e(n, \lambda_1) = \frac{1}{2} \text{erfc}\left(\sqrt{\Psi_n \lambda_1}\right)$$
Taking into account that $\lambda_1$ is a lognormal random variable, we can use the expansion of differences proposed in [20] to obtain a good approximation to the average BER as

$$P_b(n) = \frac{1}{3} \text{erfc} \left( \sqrt{\Psi_n} \right) + \frac{1}{12} \text{erfc} \left( \sqrt{3\sigma_{sh}^2\Psi_n} \right)$$

$$+ \frac{1}{12} \text{erfc} \left( -\sqrt{3\sigma_{sh}^2\Psi_n} \right) \quad (21)$$

V. NUMERICAL RESULTS

In this section we investigate the impact of different channel and system parameters on the system performance. In the following figures the parameters considered by default are: a cell layout with $Q = 91$ cells, a channel with an exponential MIP of the type $\Omega_l = \Omega_1 e^{-0.5(l-1)}$, where $\Omega_l$ is the instantaneous power of path $l$, a number of resolvable paths $L = 3$, a Nakagami fading parameter $m = 1.5$, a processing gain of $G_p = 256$, a path loss exponent of $\mu = 4$, a shadowing deviation of $\sigma_{sh} = 6dB$, a power control error deviation of $\sigma_c = 1dB$, a set of eligible BSs of $Q_c = 4$ and a packet length of $E = 1024$.

Fig.2 shows the curves of normalized throughput (number of packets per CDMA code and time slot) as a function of the cell load for different processing gains of a system stabilized using (4), it can be seen that once reached the saturation point the throughput value of all curves remains nearly constant for any cell load. All the other figures represent the variation suffered by this normalized optimum throughput value as different parameters. Fig.3 show the effect of PCE on the system throughput for different $L$ values and considering a fixed number of intercell interferers ($M_f = 20$), the figure shows two groups of curves: curves with dotted lines correspond to default channel conditions while the curves with continuous lines correspond to a worse channel ($m = 0.75$, $\mu = 3$, $\sigma_{sh} = 8$). It is clear then that a system degradation due to PCE occurs only when there are adverse channel conditions mainly when there are few paths (curve with $L=2$) resolvable in the receiver. Fig.4 shows the effect of the distance loss index $\mu$ and the shadowing $\sigma_{sh}$ over the throughput as a function of the number of intercell interferers. In that case we see a throughput degradation when $\mu \leq 3$ and $\sigma_{sh} \geq 8$. Low $\mu$ values imply that intercell interferences are less attenuated on their way to the cell-of-interest and this fact combined with an important shadowing provokes an increase of the level of interference produced by each interfering user and a degradation of the system performance when the number of interferers increase. This effect of shadowing is due to the fact that with a higher shadowing a MS has a higher probability to not be connected to the BS with the lower average attenuation as it is not one of the $Q_c$ cells, increasing in that way the power emitted by this interfering MS. The effect of the $\frac{E_b}{N_0}$ figure combined with the Nakagami parameter $m$ is also represented in Fig. 5 showing that there is a $\frac{E_b}{N_0}$ threshold that allows the correct operation of the system and that this threshold varies with the channel conditions, for example in the figure a $\frac{E_b}{N_0} = 15dB$ is required in the case of a bad channel ($m = 0.75$, worse than a Rayleigh channel) while this $\frac{E_b}{N_0}$ could be lower (around 10 dBs) for better channels ($m = 1.5-2.25$).

Finally the effect of the processing gain $G_p$ and its ability to mitigate the effect of the interferences is depicted in Fig.6. This figure shows that as well as with the EbN0, a minimum processing gain $G_p > 128$ is required to allow the correct operation of the system.
cell processing gain DS-CDMA channel degradation, due for example to a low
CDMA channel conditions except when there is a significant
used the system throughput is very robust to varying DS-
number of users in backlog but also the DS-CDMA channel
retransmission probability that takes into account not only the
system characteristics such as the processing gain or the
system is affected by the channel conditions and some key
We analyzed how the throughput of the optimally stabilized
control error on a Nakagami frequency selective environmen t.
In this paper, we have investigated the performance of
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ONCLUSIONS
VI. CONCLUSIONS
In this paper, we have investigated the performance of
a multicell S-ALOHA DS-CDMA system with fast power
control error on a Nakagami frequency selective environment.
We analyzed how the throughput of the optimally stabilized
system is affected by the channel conditions and some key
system characteristics such as the processing gain or the
number of fingers in the RAKE receiver. By using an ideal
retransmission probability that takes into account not only the
number of users in backlog but also the DS-CDMA channel
conditions we obtain the maximal achievable throughput of a
S-ALOHA DS-CDMA system for a given DS-CDMA channel.
These results can be used as an upperbound for currently used
S-ALOHA DS-CDMA systems.
The results obtained reflect that if fast power control is
used the system throughput is very robust to varying DS-
CDMA channel conditions except when there is a significant
DS-CDMA channel degradation, due for example to a low
processing gain $G_p < 128$ or an insufficient $E_b/N_0$ figure $E_b/N_0 < 
15dB$ or if a combination of the following conditions occurs:
a significant power control error ($PCE \geq 2dBs$), a high
number of intercell interferers ($M_{qT} > 20$ for any interfering
cell $q$), an important level of shadowing ($\sigma_{sh} \geq 8dBs$) and
fast fading ($m \leq 1$), a low distance loss index ($\mu \leq 3$) or a
low number of paths ($L \leq 3$).

REFERENCES

Fig. 5. Normalized optimum throughput vs the EbN0 as a function of $m$

Fig. 6. Normalized optimum throughput vs the number of intercell interferers as a function of $G_p$. 

Normalized optimum throughput as a function of $G_p$.