A SEMI-BLIND BASE STATION POWER ESTIMATION ALGORITHM FOR INTERFERENCE AWARE HSDPA RECEIVERS

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ABSTRACT

In order to mitigate multipath and inter-cell interference in a mobile terminal, the received signal statistics have to be estimated. In a Code Division Multiple Access (CDMA) system with multiple users, it is difficult to estimate all sources of interference directly. The multipath channel can be estimated using a pilot sequence, but since the pilot is code-multiplexed, it gives no indication for other code powers. We show that assuming a fixed ratio between pilot power and total power has a severe impact on throughput performance if multipath or inter-cell interference are dominant. We develop a low-complexity, semi-blind power estimation algorithm, which is optimized for minimum estimation variance and delay. The algorithm is benchmarked using the interference aware High Speed Downlink Packet Access (HSDPA) type 3i reference implementation as defined by the 3GPP standard.

1. INTRODUCTION

Signals transmitted over a multipath channel to a mobile receiver are subject to interference and fading. In order to achieve the data rates required by services such as HSDPA reliably, the equalizer attempts to reverse the effects of the multipath channel. If the channels of interfering base stations are known as well, the equalizer can exploit this information to reduce inter-cell interference. The test scenarios and reference implementation for the interference aware receiver are defined in 3GPP technical report 25.963 [6]. The document also defines a reference receiver based on the Linear Minimum Mean Square Error (LMMSE) optimization criterion.

Each Universal Mobile Telecommunications System (UMTS) base station transmits a known pilot sequence, which can be used to estimate the multipath channel. The pilot channel is transmitted simultaneously with other control and data channels. The pilot power therefore amounts to only a fraction of the total transmit power. While many test cases define $-10\,$dB pilot to total transmit power ratio, the standard does not require a fixed relationship. Indeed, while the pilot power must remain constant, the total transmit power can change almost arbitrarily (*cf.* Figure 1).

While several authors have investigated pilot-aided channel estimation and equalization for HSDPA [1–5], to the authors' best knowledge, no publications have been made which also consider the fact that the transmit power is time-variant and unknown to the receiver.

Knowledge of the transmit power is necessary to obtain the received signal's autocorrelation matrix from the pilot-aided channel estimates, however (*cf.* Equation (5)). One possible solution is to despread all codes and estimate the transmit power for each. Since the code tree allocation for other users is unknown – even the spreading factor can vary – this approach also requires a reliable code detection algorithm. Considering that this has to be done for potentially dozens of users and multiple base stations, it becomes evident that such an algorithm has significant computational complexity.

This problem can be avoided by ignoring the pilot sequence and estimating the autocorrelation matrix using the received signal's sample covariance. This approach is both inaccurate and computationally complex, however.

We will therefore develop a semi-blind approach which does not concern itself with other users' codes at all. Instead, we exploit the orthogonality of spreading codes in order to cancel the signal of one base station. The base station power can then be inferred from the difference between the remaining power and the total power.

Section 2 introduces the model used to describe the received signal. Section 3 develops a power estimation algorithm. Section 4 discusses the simulation environment and results.

Notation

$\mathcal{N}(x_0, \sigma^2)$ denotes the circular-symmetric complex Gaussian distribution with mean x_0 and variance σ^2 as defined by the probability density function

$$p(x) = \frac{1}{\pi\sigma^2}\exp(-|x-x_0|^2/\sigma^2)\ .$$

Let A be an $n \times n$ matrix with elements $a_{i,j}$, then $B = \mathrm{toeptr}_m A$ denotes the $m \times m$ Toeplitz matrix B with elements

$$b_{i,j} = \sum_{k=0}^{n-1-|i-j|} a_{\max(0,i-j)+k,\max(0,j-i)+k}\ ,$$

that is, the elements of the mth off diagonal of B have the value of the sum of the nth off diagonal of A. $\|x\| = \sqrt{x^{\mathrm{H}}x}$ denotes the 2-norm of x. E and Var denote the expectation and variance operators, respectively.

2. SYSTEM MODEL

In a scenario with N base stations we observe the received signal

$$y(n) = \sum_{k=1}^{K} h_k^{\mathrm{T}}\vec{x}_k(n) + v(n)\ ,$$

where v is an independent and identically distributed noise process, $v(n) \sim \mathcal{N}(0, \sigma_v^2)$, $\vec{x}_k(n) = (x_k(n), \ldots, x_k(n-L+1))^{\mathrm{T}}$ is the transmit signal vector of base station k at time index n, and $h_k = (h_{k,1}, \ldots, h_{k,L})^{\mathrm{T}}$ is the $L \times 1$ channel vector, where $h_{k,l}$ denotes the lth channel tap of base station k. The received signal power is $\sigma_y^2 = \mathrm{E}(|y|^2)$.

Each base station transmits a known pilot signal, which is code multiplexed as part of the transmit signal x_k. Since the pilot transmit power must remain constant, it is convenient to normalize it to one. The total transmit power $\alpha_k = \mathrm{E}(|x_k|^2)$ in this scale is therefore also the ratio of total transmit power to pilot power. While the standard specifies that the pilot power must remain constant, the total transmit power is variable due to varying cell load, power control, and bursty traffic.

Figure 1 shows live network pilot power to total receive power measurements during a bursty HSDPA transmission in the absence

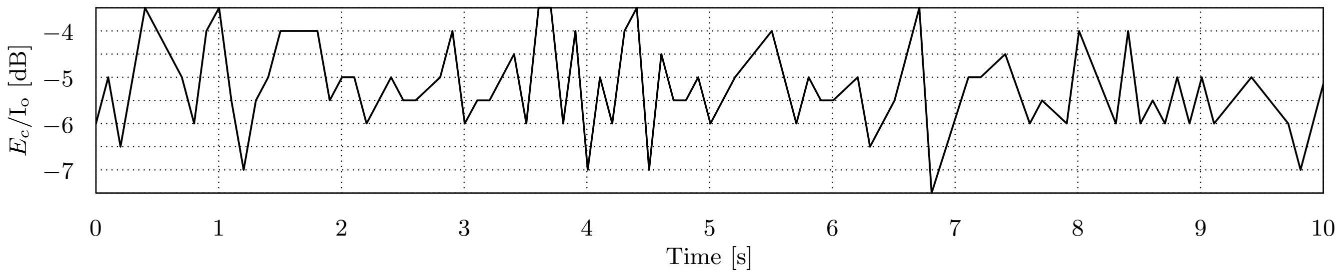


Figure 1: Live network pilot to total receive power ratio measurements during bursty HSDPA transmission.

of inter-cell interference. The measurements are averaged over 100 ms intervals. Nevertheless, the power variations due to bursty traffic are significant. The most likely cause for this behavior is a bottleneck in the network backbone.

3. POWER ESTIMATOR

By correlating with the pilot sequence of base station k, for each symbol we get the channel estimate

$$\hat{h}_{k,l} \sim \mathcal{N}\left(h_{k,l}, \sigma_{k,l}^2\right)$$

with variance

$$\sigma_{k,l}^2 = \frac{1}{\mathrm{SF}}(\sigma_y^2 - \alpha_k \left|h_{k,l}\right|^2)\,, \tag{1}$$

where SF is the spreading factor. Multipath and inter-cell interference at the correlator output are approximated as Gaussian noise. In order to reduce the estimators' complexity, we will assume that the estimation noise $z_{k,l} = \hat{h}_{k,l} - h_{k,l}, l = 1, \ldots, L$ is uncorrelated.

Figure 2 illustrates the power proportions of the signals y and $\hat{h}$ on the left- and right-hand-side bars, respectively. By estimating the noise power of $\hat{h}_{k,l}$ and the power of y, we therefore get a relation for α_k.

Rearranging Equation (1) and replacing σ_y^2 with the sample variance $\hat{\sigma}_y^2 = \frac{1}{\mathrm{SF}} \sum_{n=1}^{\mathrm{SF}} |y(n)|^2$ yields the following estimate for α_k.

$$\hat{\alpha}_{k,l} = \frac{1}{\left|h_{k,l}\right|^2}\left(\hat{\sigma}_y^2 - \mathrm{SF}\left|z_{k,l}\right|^2\right) \tag{2}$$

This estimate is unbiased, $\mathrm{E}(\hat{\alpha}_{k,l}) = \alpha_k$, and has variance

$$\begin{aligned}
\mathrm{Var}(\hat{\alpha}_{k,l}) &= \frac{1}{\left|h_{k,l}\right|^4}\left(\mathrm{Var}(\hat{\sigma}_y^2) + \mathrm{SF}^2\,\mathrm{Var}(\left|z_{k,l}\right|^2)\right) \\
&= \frac{1}{\left|h_{k,l}\right|^4}\left(\frac{1}{\mathrm{SF}}\sigma_y^4 + \mathrm{SF}^2\sigma_{k,l}^4\right) \\
&= \frac{1}{\left|h_{k,l}\right|^4}\left(\frac{1}{\mathrm{SF}}\sigma_y^4 + (\sigma_y^2 - \alpha_k\left|h_{k,l}\right|^2)^2\right) \\
&\leq 1/\left|h_{k,l}\right|^4 (1/\mathrm{SF} + 1)\,\sigma_y^4 \\
&\approx \sigma_y^4/\left|h_{k,l}\right|^4\,,
\end{aligned}$$

where we have used that the modulus squared of a zero-mean complex Gaussian random variable $X \sim \mathcal{N}(0, \sigma^2)$ has variance $\mathrm{Var}(|X|^2) = \sigma^4$. This estimate assumes that the channel is known ideally, but scaled with the pilot channel power, as it would be observed by a real channel estimator.

Using maximum ratio combining (MRC) with weights

$$\gamma_{k,l} = (\mathrm{Var}(\hat{\alpha}_{k,l}))^{-1} / \sum_{l=1}^{L} (\mathrm{Var}(\hat{\alpha}_{k,l}))^{-1}$$

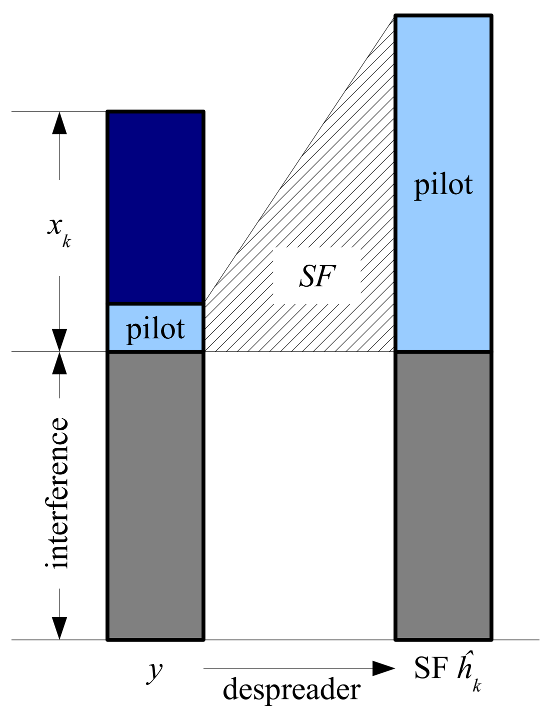


Figure 2: Power proportions of total receive signal y (left-hand-side) and pilot despreader output (right-hand-side).

we get the estimator

$$\tilde{\alpha}_k = \sum_{l=1}^{L} \gamma_{k,l} \hat{\alpha}_{k,l} \tag{3}$$

which is again unbiased and has variance

$$\mathrm{Var}(\tilde{\alpha}_k) \le \sigma_y^4 / \sum_{l=1}^{L} \left|h_{k,l}\right|^4 , \tag{4}$$

where the inequality becomes equality asymptotically as $\mathrm{SF} \to \infty$ and $\alpha_k \left\|h_k\right\|^2 / \sigma_y^2 \to 0$. Since α_k is required to compute the MRC weights, a preliminary estimate has to be used in its place.

Equation (4) implies that the standard deviation of $\tilde{\alpha}_k/\alpha_k$ is approximately the inverse of the instantaneous SNR, which can become quite large at fading dips. At the same time, transmit power can change due to power control and bursty traffic. If more data is transmitted over the air than the backbone can provide, the transmit power can change significantly from subframe to subframe, depending on whether or not an HSDPA transport block is scheduled for transmission.

We therefore require an adaptive filter, which takes instantaneous estimation variance into account. We optimize it to minimize both estimation variance and filter delay. Let $\beta_n, n = 1, 2, \ldots,$ be the IIR filter coefficient at pilot symbol index n, and start out with $\beta_0 = 1$. Then, the estimate at the filter output is

$$\bar{\alpha}_n = \beta_n \tilde{\alpha}^{(n)} + (1-\beta_n)\bar{\alpha}_{n-1} ,$$

where we have dropped the base station index k, and $al\tilde{p}ha^{(n)}$ denotes the power estimate at pilot symbol index n. Given the estimation variance of the previous filter output $V_{\mathrm{old}} = \mathrm{Var}(\bar{\alpha}_{n-1})$ and a new estimate with the instantaneous variance $V_{\mathrm{new}} = \mathrm{Var}(\tilde{\alpha}^{(n)})$, we have the variance

$$\mathrm{Var}(\bar{\alpha}_n) \approx \beta^2 V_{\mathrm{new}} + (1-\beta)^2 V_{\mathrm{old}} ,$$

which achieves its minimum

$$V_{\mathrm{min}} = V_{\mathrm{new}} \beta_{\mathrm{min}}$$

at $\beta_{\mathrm{min}} = V_{\mathrm{old}}/(V_{\mathrm{new}} + V_{\mathrm{old}})$. This is optimal with respect to variance minimization. The filter delay, however, will become infinitely large, since forgetting a past estimate would never decrease variance. We therefore specify a variance target V_{max}, beyond which the filter should never try to minimize. The corresponding optimal coefficient is

$$\beta = \begin{cases} \beta_{\mathrm{min}} & \text{if } V_{\mathrm{min}} > V_{\mathrm{max}} , \\ 1 & \text{if } V_{\mathrm{new}} < V_{\mathrm{max}} , \\ \beta_{\mathrm{min}} + \sqrt{\frac{V_{\mathrm{max}} - V_{\mathrm{min}}}{V_{\mathrm{new}} + V_{\mathrm{old}}}} & \text{otherwise.} \end{cases}$$

As a measure for delay we define

$$\Delta_n = \sum_{m=1}^{n} m a_{m,n} ,$$

where $a_{0,n} = \beta_n, a_{m,n} = (1-\beta_{n-1})a_{m-1,n-1}$ for $m = 1, \ldots, n$ are the coefficients of an equivalent FIR filter at symbol index n. The filter delay can be computed recursively using

$$\Delta_n = (1-\beta_n)(\Delta_{n-1} + 1) .$$

In order to optimize the estimation variance independently of the pilot power we define the normalized variance $V'_{\mathrm{max}} = V_{\mathrm{max}} \bar{\alpha}^2$, using a previous estimate for α.

4. SIMULATION RESULTS

In order to evaluate the power estimation algorithm performance we implemented an HSDPA receiver capable of "two-branch interference mitigation" as defined in [6]. Maximum ratio combining is performed over both receive antennas, analogously to Equation (3).

The simulation starts recording statistics only after the power estimation filter has settled.

The equalizer is a two-branch, two times oversampled 20-chip Linear Minimum Mean Square Error (LMMSE) equalizer, as defined in [6], i.e. an Finite Impulse Response (FIR) filter of order Q with coefficients f defined as the solution to the equation

$$(C_y + \eta I) f = r_{yx}$$

with regularization factor η (explained below). The autocorrelation matrix C_y and the cross-correlation vector r_{yx} of this equation are computed using the channel and power estimates, i.e.

$$C_y = \sum \alpha_k H_k H_k^{\mathrm{H}} + \sigma_v^2 I , \tag{5}$$

where H_k is the channel convolution matrix of base station k, $r_{yx} = (r_{yx,1}, \ldots, r_{yx,Q})^{\mathrm{T}}$, and

$$\begin{aligned} r_{yx,q} &= \mathrm{E}(y(n+q-\lfloor Q/2 \rfloor)x_1(n)) \\ &= \alpha_1 \begin{cases} h_{1,q-\lfloor Q/2 \rfloor} & \text{if } q > \lfloor Q/2 \rfloor , \\ 0 & \text{otherwise .} \end{cases} \end{aligned}$$

The equalizer performs spatial interference suppression. Please see [1–3] for more details on the LMMSE equalizer. In case of real power estimation, α in the above equations is substitued by the corresponding estimate $\bar{\alpha}$. The noise power σ_v^2 is substituted by the estimator $\hat{\sigma}_v^2 = \hat{\sigma}_y^2 - \sum_{k=1}^{K} \bar{\alpha}_k \sum_{l=1}^{L} \left|h_{k,l}\right|^2$.

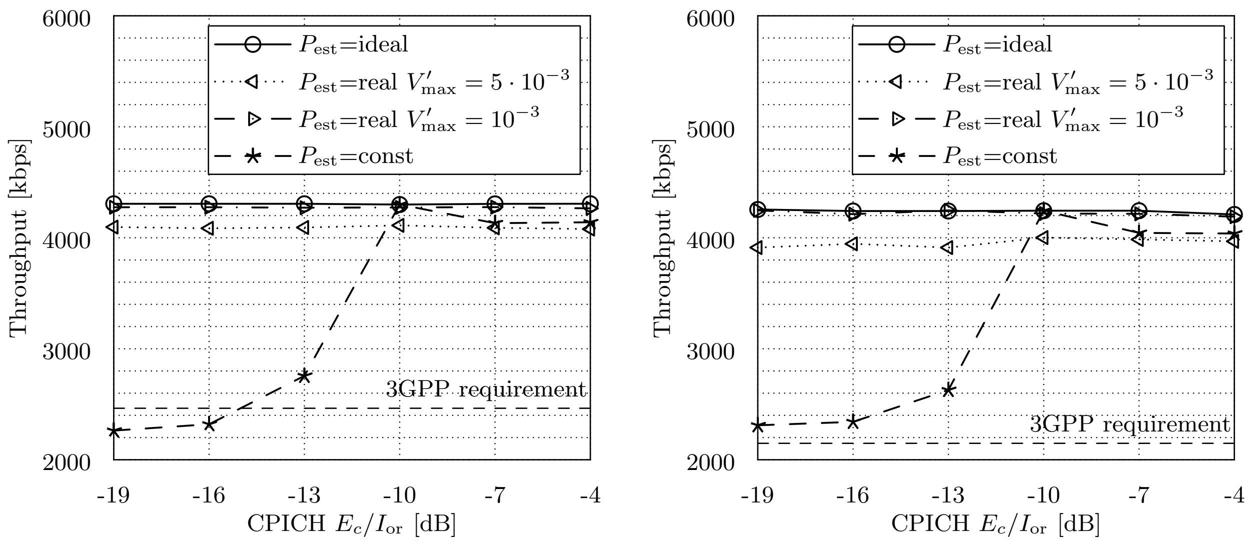
We assume that h_k is known to the receiver. At low to medium mobile speed, the channel can be estimated quite accurately by averaging the pilot correlator output $z_{k,l}$ over multiple symbols. For high mobile speeds, such as $120\,\mathrm{km/h}$, this assumption is too optimistic. But we would like to demonstrate that the power estimation algorithm works independently of the fading conditions.

Note that the simulator actually samples the received signal with oversampling factor 2 and it precedes the equalizer with a root raised cosine (RRC) matched filter. The signal is also received via two antennas. As a result, the FIR filter has 80 taps total, one per chip, polyphase and antenna. For notational convenience, however, the equations in this paper do not consider oversampling. Please confer [6] for a more detailed description.

Note also that the receiver uses a finite channel window length of $L = 20$ chips. Due to the RRC pulse shape, the actual channel is longer than that. In order to account for this error, we therefore add the regularization parameter $\eta = 0.05$ to the diagonal of the autocorrelation matrix.

H-Set 6 denotes the test case configuration and is defined in [7]. It specifies 10 multicodes and 6438 bits transport block size for QPSK, 8 multicodes and 9377 bits transport block size for 16QAM. These transport block sizes correspond to a maximum throughput of $3.2\,\mathrm{MBit/s}$ and $4.7\,\mathrm{MBit/s}$, respectively. The serving base station continually transmits at these data rates. Apart from incremental redundancy due to the Hybrid Automatic Repeat Request (HARQ) protocol, no adaptive coding is performed. The HARQ buffer size is 19200 softbits. The remaining transmit power, after subtracting CPICH and HS-PDSCH power, is filled with the Orthogonal Channel Noise Simulator (OCNS) signal.

Figure 3 plots throughput performance of a single base station scenario for Pedestrian B and Vehicular A power delay profiles at 3 and 120 km/h, respectively. The parameter Common Pilot Channel (CPICH) $E_c/\mathrm{I_{or}} = \alpha_1^{-1}$ specifies the relative pilot to total transmit power. The P_{est}=const curve assumes CPICH $E_c/\mathrm{I_{or}} = -10\,\mathrm{dB}$, unless the resulting signal power would exceed the total receive power.



(a) Pedestrian B, 3 km/h

(b) Vehicular A, 120 km/h

Figure 3: Throughput performance, H-Set 6, 16QAM, $\hat{\mathrm{I}}_{\text{or}}/\mathrm{I}_{\text{oc}} = 10\,\text{dB}$, HS-PDSCH $E_c/\mathrm{I}_{\text{or}} = -3\,\text{dB}$

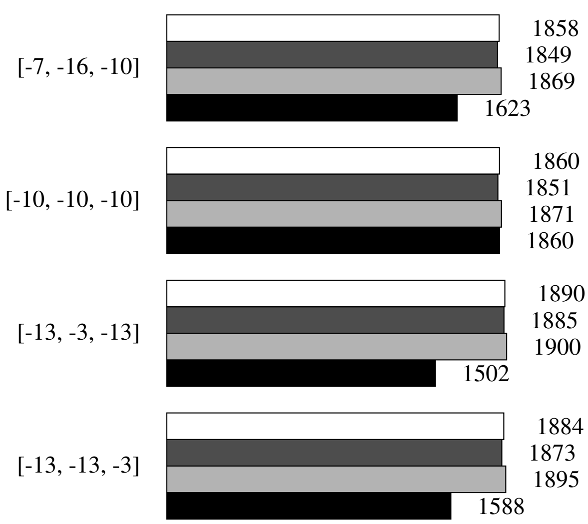


Figure 4: Throughput performance with 2 interfering base stations $\mathrm{DIP}_1 = -2.75\,\text{dB}$, $\mathrm{DIP}_2 = -7.64\,\text{dB}$ for different CPICH $E_c/\mathrm{I}_{\text{or}}$ configurations $[\alpha_1^{-1}, \alpha_2^{-1}, \alpha_3^{-1}]$ in dB, H-Set 6, QPSK, $\hat{\mathrm{I}}_{\text{or}}/\mathrm{I}_{\text{oc}} = 0\,\text{dB}$, HS-PDSCH $E_c/\mathrm{I}_{\text{or}} = -3\,\text{dB}$. The bar colors corresponds to the algorithms P_{est}=const ■, P_{est}=real with $V'_{\max} = 10^{-3}$ ■ or $V'_{\max} = 5 \cdot 10^{-3}$ ■, and P_{est}=ideal □.

$\hat{\mathrm{I}}_{\text{or}}/\mathrm{I}_{\text{oc}}$ specifies the average serving cell (i.e., base station 1) to interference power ratio. In this case, the entire interference $\mathrm{I}_{\text{oc}} = \sigma_v^2$ is modelled as white Gaussian noise. In this scenario, performance is sensitive to power estimation, because it is used to estimate the SNR. If SNR is underestimated, the equalizer cannot properly mitigate multipath interference. If SNR is overestimated, the equalizer does not sufficiently account for noise amplification.

Figure 4 shows throughput performance in a scenario with two interfering base stations for different CPICH $E_c/\mathrm{I}_{\text{or}}$ configurations $[\alpha_1^{-1}, \alpha_2^{-1}, \alpha_3^{-1}]$. The dominant interferer proportion (DIP) values specify the average observed power $\hat{\mathrm{I}}_{\text{or,k+1}}$ of the interfering base station k at the receiver, i.e. $\hat{\mathrm{I}}_{\text{or,k}} = \alpha_k \, \mathrm{E}(\|h_k\|^2)$ and $\mathrm{DIP}_k = \hat{\mathrm{I}}_{\text{or,k+1}}/\mathrm{I}_{\text{oc}}$. The residual interference $\mathrm{I}_{\text{oc}} - \sum_{k=2}^{K} \hat{\mathrm{I}}_{\text{or,k}} = \sigma_v^2$ is modelled as white Gaussian noise.

Depending on the scenario, the fixed power assumption either under- or overestimates the interference. Either way, the estimation error causes a performance degradation.

Throughput performance is therefore sensitive to power estimation if either multipath or inter-cell interference is dominant.

Figure 5 plots average power estimation filter delay over base station power. While the average delay is a single-digit number of subframes at 10 dB SNR, at 0 dB SNR, as in the type 3i scenario, the weakest base station requires hundreds of subframes (one subframe is 2 ms) averaging delay. Since throughput performance is less sensitive to power estimation error at low SNR, $V'_{\max}$ can be increased in order to reduce delay. The best tradeoff depends on the base station's scheduling behavior and will have to be found in field tests.

In order to simulate a bursty traffic scenario as observed in Figure 1, we consider a scenario with only one interfering base station of average strength equal to the serving cell, without any residual other cell interference. The OCNS is turned off in the interfering base station. Its maximum load is therefore the sum of CPICH $E_c/\mathrm{I}_{\text{or}} = -10\,\text{dB}$ and HS-PDSCH $E_c/\mathrm{I}_{\text{or}} = -3\,\text{dB}$ from a data channel transmitted to a mobile station connected to the interfering cell. This data channel is periodically transmitted for t subframes and then turned off for $T - t$ subframes. The performance results for this scenario are shown in Figure 6 for different duty cycles $[t\ T]$ of the interfering data channel. Depending on the duty cycle, $V'_{\max}$ is either too large or too small. Nevertheless, the performance is close to a receiver which knows the transmit power, and far exceeds the performance of a receiver which assumes constant transmit power.

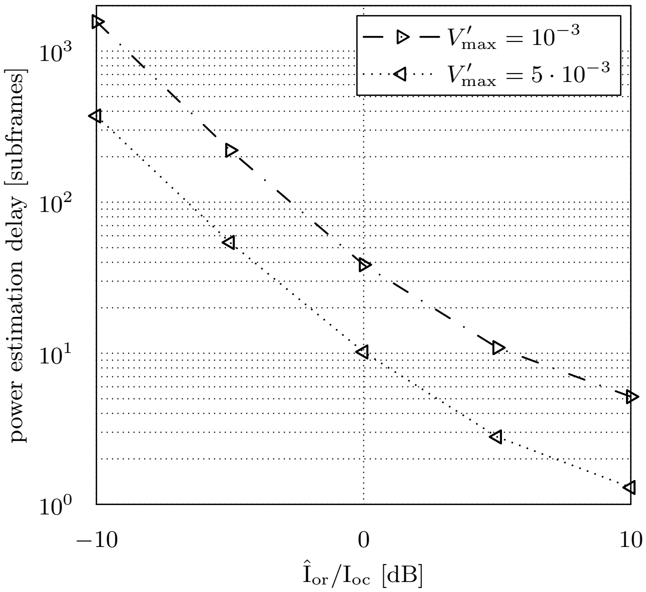


Figure 5: Average power estimation filter delay, CPICH $E_c/\mathrm{I}_{\mathrm{or}} = -10\,\mathrm{dB}$

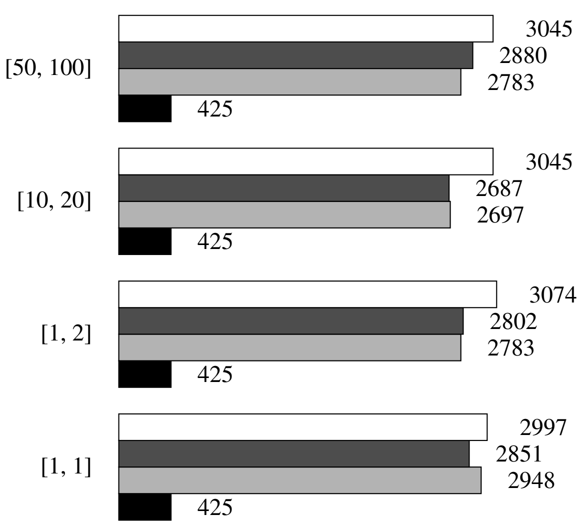


Figure 6: Throughput performance with bursty traffic on one interfering base station with duty cycle $[t,\, T]$ and relative power $\mathrm{DIP}_1 = 0\,\mathrm{dB}$, H-Set 6, QPSK, $\hat{\mathrm{I}}_{\mathrm{or}}/\mathrm{I}_{\mathrm{oc}} = 0\,\mathrm{dB}$, HS-PDSCH $E_c/\mathrm{I}_{\mathrm{or}} = -3\,\mathrm{dB}$, CPICH $E_c/\mathrm{I}_{\mathrm{or}} = \alpha^{-1} = -10\,\mathrm{dB}$, no OCNS, in a 30 km/h flat fading channel. The bar colors corresponds to the algorithms P_{est}=const, P_{est}=real with $V'_{\max} = 10^{-3}$ or $V'_{\max} = 5 \cdot 10^{-3}$, and P_{est}=ideal.

5. CONCLUSION

It was shown that power estimation is necessary to avoid severe performance degradation. We developed a low-complexity general-purpose power estimation algorithm for CDMA systems with code-multiplexed pilot channels. It can be used by HSDPA receivers which are based on LMMSE equalizers in order to estimate serving cell and inter-cell interference power with little performance loss compared to ideal knowledge of the power.

For weak base stations, however, a significant amount of averaging delay is necessary in order to achieve the required accuracy.

Items for further study could be the effects of real channel estimation error, as well as potential improvements by taking correlation of instantaneous power estimates into account.

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