Residual Interference Modeling in WCDMA Serial Interference Cancellation Receivers

Zaher Dawy, Saša Davidović
Institute for Communications Engineering (LNT)
Munich University of Technology (TUM)
Arcisstr. 21, 80290 Munich, Germany
Email: Dawy@ei.tum.de, sasad@eikon.tum.de

Alexander Seeger
Information and Communication Mobile
Siemens AG
Hofmannstr. 51, 81379 Munich, Germany
Email: Alexander.Seeger@icn.siemens.de

***Abstract*— Serial interference cancellation (SIC) is a very promising receiver structure for enhancing the uplink capacity of WCDMA cellular systems. It can be implemented easily in practice with low complexity compared to other multiuser detection techniques. In this work, we define and evaluate an interference cancellation factor that models the amount of residual interference after applying SIC. The adopted system model resembles the WCDMA FDD mode of UMTS. We show that the amount of residual interference is a function of the receiver structure and a set of different system parameters. Performance results of two proposed evaluation methods are presented and compared with computer simulations. Using the calculated interference cancellation factor, it can for example be shown that applying SIC with soft detection and two cancellation stages can nearly double the uplink user capacity of a WCDMA cellular system.**

I. Introduction

WCDMA has been selected for the FDD mode of UMTS due to its service flexibility and improved performance over second generation systems. Due to asynchronous transmission and multipath fading, the uplink receiver in WCDMA is subject to multiple–access interference (MAI). In a conventional WCDMA system, each user is detected treating all other users as noise. This basic scheme has a limited spectral efficiency and suffers from the near–far effect [1]. Higher spectral efficiency can be achieved by reducing the MAI. Serial interference cancellation (SIC) is a very promising multiuser detection (MUD) technique for enhancing the uplink capacity of WCDMA cellular systems [2], [3], [4]. The major advantage of SIC is its relatively low complexity, which is linear in the number of users, compared to other MUD techniques.

In this work, we define and evaluate an interference cancellation factor, denoted by λ factor, which models the amount of residual interference after applying SIC as a function of different system parameters and the receiver structure. Some direct applications of the evaluated interference cancellation factor for SIC receivers are the following:

- Makes the computation of the log–liklihood ratios (LLR) more exact. The LLR values are required by the canceler when the soft detected feedback function is used [4].
- Allows the computation of the optimal required received powers of the different users which enables the implementation of SIC with only one cancellation stage [5].
- Helps in modeling SIC receivers in the system level. This leads to an easy way to evaluate the user capacity and the system coverage when SIC receivers are used.
- Can be used as reliability information for optimal combining in SIC receivers with multiple cancellation stages [6].
- Can be used as a figure of merit to compare different SIC structures with different system parameters.

Section II introduces the uplink system model with the conventional WCDMA receiver structure. Section III presents the main concept behind SIC. In Section IV, different ways to evaluate the interference cancellation factor are explained and performance results for different scenarios are presented. Finally, some conclusions are drawn in Section V.

II. System Model

Consider the uplink of a WCDMA communication system (FDD mode of UMTS) composed of K synchronous users as shown in Fig. 1. The uplink transmission is divided into 10 ms frames, where each frame is composed of 15 slots and each slot is composed of 2560 chips. Each user has a data and control channel that are spread using orthogonal sequences and multiplexed using dual BPSK [7]. The control channel is used to transmit pilot bits for channel estimation. The data channel is used to transmit the encoded information bits. A rate 1/3 memory 8 convolutional encoder with generator polynomial $[557_8\ 663_8\ 711_8]$ and a random interleaver are used. For user k, the i^{th} encoded data bit, $b_{k_i}, b_{k_i} \in \{-\sqrt{P_k}, +\sqrt{P_k}\}$, is spread on the real component with a pre–assigned spreading sequence $\mathbf{s}_k = (s_{k_1}, s_{k_2}, \ldots, s_{k_{N_d}}),\ s_{k_n} \in \{-1, +1\}$. Similarly, the i^{th} control bit c_{k_i}, $c_{k_i} \in \{-\beta_c\sqrt{P_k}, +\beta_c\sqrt{P_k}\}$, is spread on the imaginary component with a spreading sequence $\mathbf{t}_k = (t_{k_1}, t_{k_2}, \ldots, t_{k_{N_c}}), t_{k_n} \in \{-1, +1\}$. The resulting modulated signal for each data bit (N_d chips) is independently scrambled with a complex random scrambling sequence $\mathbf{v}_k = (v_{k_1}, v_{k_2}, \ldots, v_{k_{N_d}}), v_{k_n} \in \{(\pm 1 \pm j)/\sqrt{2}\}$. Note that the power on the data and control channels for user k are equal to P_k and $\beta_c^2 P_k$, respectively, and the number of data and control bits per slot depend on the spreading factors N_d and N_c, respectively. The total received signal for the n^{th} chip of the i^{th} bit, r_n, is given by:

$$r_n = \sum_{k=1}^{K} a_{k_i} \cdot v_{k_n} \cdot \left(b_{k_i} s_{k_n} + j c_{k_i} t_{k_n} \right) + z_n, \quad (1)$$

where a_{k_i} is the single–path channel response of user k which is assumed to be fixed over the bit duration with $\mathrm{E}\{|a_{k_i}|^2\} = 1$, and z_n is complex additive white Gaussian noise with zero mean and variance σ^2 per dimension.

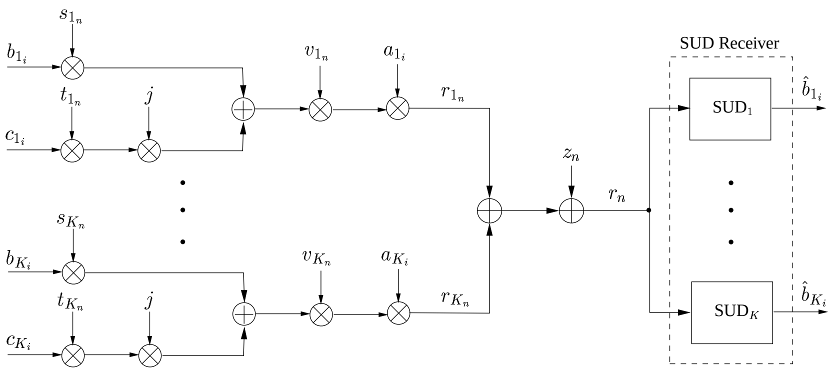

Fig. 1. WCDMA uplink system model with single user detection (SUD).

The conventional single user detector (SUD) receiver despreads and descrambles each user with the same spreading and scrambling codes used at the transmitter treating all other users as interference. Then, a Rake receiver detects the user signal and outputs a soft estimate of each transmitted data bit. Assuming ideal channel estimation, the detected signal of user k after SUD is given by:

$$\hat{b}_{k_i} = |a_{k_i}|^2 b_{k_i} + |a_{k_i}| z_{k_i}, \qquad (2)$$

where z_{k_i} is modeled by the central limit theorem for large spreading factor, N_d, as a zero mean real Gaussian variable with variance $\sigma^2_{\text{SUD},k_i}$ given by:

$$\sigma^2_{\text{SUD},k_i} = \frac{1}{N_d}\left(\sigma^2 + \frac{1}{2}\sum_{\substack{l=1\\ l\neq k}}^{K} |a_{l_i}|^2 P_l (1+\beta_c^2)\right). \qquad (3)$$

The system model can be easily extended to a multipath channel by taking the sum over all the paths for interference estimation and performing maximum ratio combining in the Rake receiver. The SUD receiver is clearly limited by the multiple–access interference and, thus, there is a need to consider more advanced receiver structures that achieve better performance.

III. Serial Interference Cancellation (SIC)

The main principle behind SIC is the following: first order the users according to a given criterion, e.g., in a decreasing order of received powers. Perform SUD for the first user, obtain an estimate of his transmitted signal using a feedback decision function, reconstruct his received signal, and subtract his contribution (data and control channel) from the total received signal. Start the process again with the second user until all users are detected. During this first stage, the kth user in the cancellation chain has part of the interference from the previous $k-1$ users canceled, and sees full interference only from the remaining $K-k$ users. This procedure can be repeated over multiple stages. The general structure for stage s of a SIC receiver is depicted in Fig. 2. For the first stage, $s=1$, $\tilde{r}^0_n = r_n$ and $\hat{r}^0_{k_n} = 0$, $1 \leq k \leq K$. In the sequel, we assume conventional power control with all users received with the same power, $P_k = P$ for $1 \leq k \leq K$. Therefore, we assume that enough cancellation stages, S ($S \geq 2$), are performed to guarantee symmetric conditions to all users.

The residual interference after the cancellation of the estimated signal of user l, $\hat{r}_{l_n}$, is given by:

$$o_{l_n} = r_{l_n} - \hat{r}_{l_n} = v_{l_n} a_{l_i} (b_{l_i} - \tilde{b}_{l_i}) s_{l_n}, \qquad (4)$$

where $\tilde{b}_{l_i}$ is the output of the feedback decision function, $f(\hat{b})$. Due to SIC, the variance of the noise term seen by user k in (2), z_{k_i}, is modified and can be calculated and modeled as:

$$\begin{aligned}
\sigma^2_{\text{SIC},k_i} &= \frac{1}{N_d}\left(\sigma^2 + \frac{1}{2}\sum_{\substack{l=1\\ l\neq k}}^{K} |a_{l_i}|^2 (b_{l_i} - \tilde{b}_{l_i})^2\right) \\
&\triangleq \frac{1}{N_d}\left(\sigma^2 + \frac{1}{2}\sum_{\substack{l=1\\ l\neq k}}^{K} \lambda_l P_l (1+\beta_c^2)\right) \\
&= \frac{1}{N_d}\left(\sigma^2 + \frac{1}{2}\lambda (K-1) P (1+\beta_c^2)\right), \qquad (5)
\end{aligned}$$

where λ_l is the average interference cancellation factor defined as the ratio between the average residual interference power and the total received power of user l. Due to the symmetric conditions of all the users, $\lambda_l = \lambda$ for $1 \leq l \leq K$, and, thus, $\sigma^2_{\text{SIC},k_i} = \sigma^2_{\text{SIC}}$. Having $\lambda = 1$ means that no interference is canceled (SUD) while having $\lambda = 0$ means that perfect cancellation is done. The main contribution of this work is to evaluate the value of λ as a function of different system parameters and the SIC receiver structure.

IV. Residual Interference in SIC Receivers

In this section, we propose two methods to evaluate the λ factor for SIC receivers.

A. *Method I: Calculation of SIC λ factor*

Using (5), λ is defined as:

$$\lambda = \lambda_l = \frac{\mathrm{E}\{|a_{k_i}|^2 (b_{k_i} - \tilde{b}_{k_i})^2\}}{P_k (1+\beta_c^2)} \triangleq \frac{\Gamma}{P(1+\beta_c^2)}, \qquad (6)$$

where Γ can be calculated depending on the fading distribution, system parameters, and the used feedback decision function, $f(\hat{b})$, which maps the soft values at the

Top

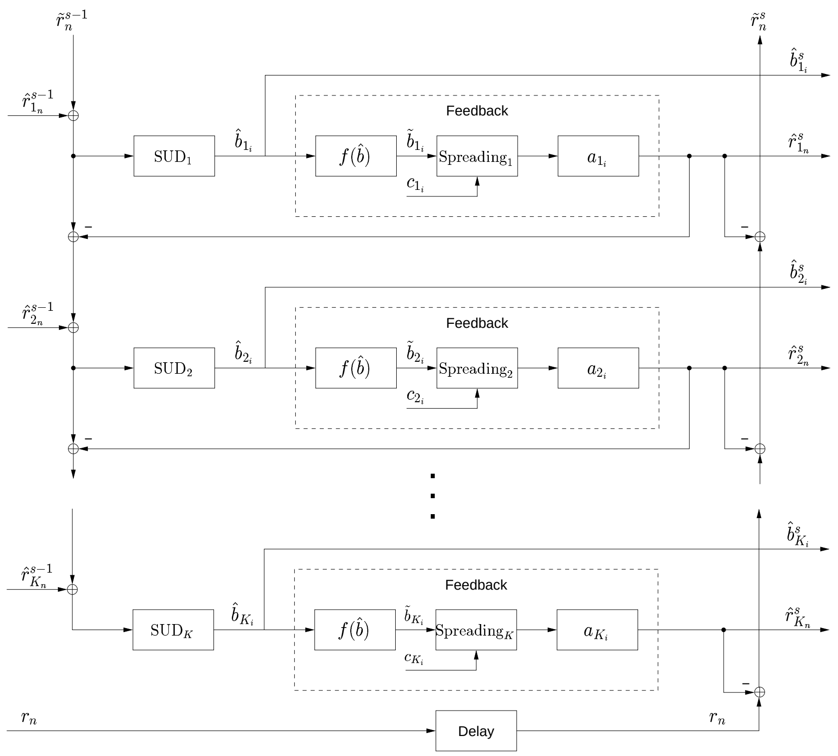

Fig. 2. Detailed structure of stage s of a SIC receiver.

output of the SUD block, $\hat{b}_{k_i} \in (-\infty, +\infty)$, to an estimate, $\tilde{b}_{k_i} \in [-\sqrt{P_k}, +\sqrt{P_k}]$, of the transmitted signal, $b_{k_i} \in \{-\sqrt{P_k}, +\sqrt{P_k}\}$ [4]. Results are presented for three different feedback decision functions.

1) Hard Detected Feedback: The hard detected feedback function utilizes only the sign of the detected soft data bit estimate. It is given by $\tilde{b}_{k_i} = f(\hat{b}_{k_i}) = \sqrt{P_k}\mathrm{sign}(\hat{b}_{k_i})$. The main drawback of this mapping is ignoring the amplitude of the soft bit which leads to doubling the residual interference in case of a wrong decision. On the other hand, this mapping has low implementation complexity. The value of Γ in (6) with hard detected feedback over an AWGN channel is calculated as:

$$\begin{aligned} \Gamma_{\text{HDF}} &= 4P \cdot \mathrm{E}\{|a_{k_i}|^2 p_e(\gamma)\} \\ &= 4P \cdot \mathrm{Q}\left(\sqrt{\frac{P}{\sigma^2_{\text{SIC}}}}\right), \end{aligned} \tag{7}$$

where $p_e(\gamma)$ is the probability of hard detection error at a signal to interference and noise ratio γ, σ^2_{SIC} is given by (5), and $\mathrm{Q}(x)$ is the error Q–function. Thus, given the needed system parameters and a required value of P, λ can be calculated iteratively using (6) and (7).

2) Soft Detected Feedback: A more accurate decision function can be used which takes into account the reliability of the soft data bits and minimizes the mean square error (MSE) between the transmitted signal and the estimated signal given the received signal. The solution to this classical minimization problem is calculated as:

$$\tilde{b}_{k_i} = \sqrt{P_k}\tanh\left(\frac{L_{k_i}}{2}\right) = \sqrt{P_k}\tanh\left(\frac{\sqrt{P_k}}{\sigma^2_{\text{SIC},k_i}} \cdot \hat{b}_{k_i}\right), \tag{8}$$

where L_{k_i} is the log–likelihood ratio (LLR) value of the detected symbol of user k. The soft detected feedback function gives a better estimate than the hard detected feedback function, but is a little more complex to implement and depends on the channel estimates which are assumed in this work to be known perfectly at the receiver. The detected values of user k can be modeled as $\hat{b}_{k_i} \sim \mathcal{N}\left(|a_{k_i}|^2 \cdot b_{k_i}, |a_{k_i}|^2 \cdot \sigma^2_{\text{SIC}}\right)$. Therefore, the operand of the tanh function in (8) for $b_{k_i} = +\sqrt{P}$ has a Gaussian distribution with

$$\mu_x = \sigma_x^2 = \frac{|a_{k_i}|^2 P}{\sigma^2_{\text{SIC}}}. \tag{9}$$

The output distribution of the tanh function $\tilde{t}_k$ with a Gaussian operand is given by [8]:

$$f_{\tilde{T}_k}(\tilde{t}_k) = \frac{1}{\sqrt{2\pi\sigma_x^2}} \cdot \frac{1}{1-\tilde{t}_k^2} \mathrm{e}^{-\frac{1}{2\sigma_x^2}\left(\tanh^{-1}(\tilde{t}_k)-\mu_x\right)^2}. \tag{10}$$

Taking into account the symmetry of the Gaussian distribution and the tanh function, the value of Γ in (6) for SIC with soft detected feedback over AWGN channel can be calculated as:

$$\Gamma_{\text{SDF}} = P\left(1 - 2\int_{-1}^{1} \tilde{t}_k f_{\tilde{T}_k}(\tilde{t}_k) d\tilde{t}_k + \int_{-1}^{1} \tilde{t}_k^2 f_{\tilde{T}_k}(\tilde{t}_k) d\tilde{t}_k\right). \tag{11}$$

Therefore, the value of λ can be calculated iteratively using (6) and (11) with the help of numerical integration.

3) Hard Decoded Feedback: The received bits of each user are channel encoded before transmission, thus, hard output channel decoding can be deployed in the feedback function which takes advantage of the error correction capabilities of the used code. The data estimates in this case are very reliable, but require very high computational complexity. The calculation of λ in this case is not possible since there is no closed form tight bound on the performance of the used code. The union bound was used to give an upper bound on the value of λ. Results have shown that the bound obtained is very loose especially for the BER range of practical interest.

We have extended the calculation of method I to multipath fading channels. This can be done by averaging the value of Γ in (6) over the fading distribution which is known for the case of multipath Rayleigh fading channels [9].

B. Method II: Estimation of SIC λ factor

The performance of cellular communication systems is measured by means of link level and system level simulations. The simulations are carried out in two levels due to the complexity of modeling the whole system into a single simulator. Link level simulators evaluate the performance of a radio link with all its details, where the output is usually a set of curves giving the BER as a function of the SNR (E_b/N_o). Using the output of the link level simulations and assuming the residual interference to be Gaussian noise, the λ factor can be estimated as:

$$\lambda = \frac{\frac{1}{(E_b/N_o)_{\text{su}}} - \frac{1}{(E_b/N_o)_{\text{sic}}}}{(K-1)(1+\beta_c^2)(R/N_d)}, \qquad (12)$$

where $(E_b/N_o)_{\text{su}}$ and $(E_b/N_o)_{\text{sic}}$ are the required SNR to achieve a target BER for the single user case and the multiuser case with SIC, respectively, and R is the channel coding rate. The importance of this method is its independence of the used receiver structure which is reflected by the E_b/N_o values to achieve the target BER. On the other hand, it requires the availability of link level simulation results.

C. Performance Results

In this section, we evaluate the value of the λ factor using the two proposed methods for SIC receivers with the three considered feedback decision functions. The used system parameters are spreading factor $N_d = 8$, $\beta_c = 1/3$, and two cancellation stages ($S = 2$). In addition to the AWGN channel, we present results for a three path Rayleigh fading channel. The multipath channel has the same power on each path with constant fading per slot (2560 chips) and independent fading from slot to slot. The evaluated values are also compared with results obtained via computer simulations. Using link level simulation results, Fig. 3 presents the required E_b/N_o values to achieve a target BER of 10^{-3} for different number of users and feedback decision functions for SIC and SUD. The first result to be noticed is that SIC with the three feedback functions performs better than SUD, and that decoded feedback performs better than soft detected feedback which in turn is better than hard detected feedback. Moreover, the E_b/N_o required to achieve a target BER of 10^{-3} for the AWGN channel is lower than that for the three path fading channel.

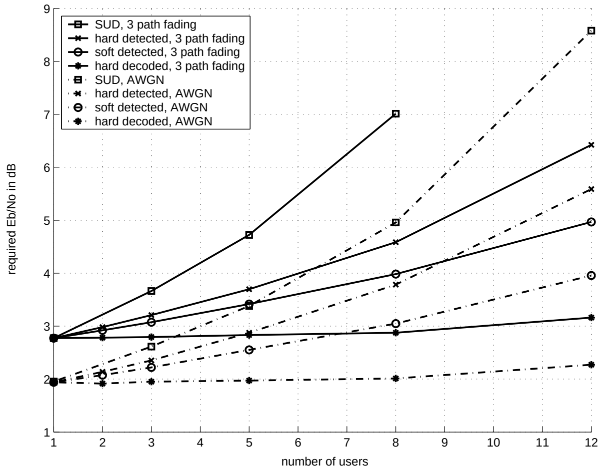

Fig. 3. Required E_b/N_o in dB to achieve a target BER of 10^{-3}.

Fig. 4 and Fig. 5 show the evaluated and simulated values of λ for the AWGN channel and the three path fading channel, respectively. Results obtained using method I nearly coincide with the simulation results, while results obtained using method II have some deviation. The reason for this is that method II estimates λ by explicitely assuming the interference to be additive Gaussian noise which in reality is not exactly true but is an approximation. On the other hand, method I calculates the value of λ taking into account the operation of the feedback decision functions in a precise way and, thus, it performs very near to the simulation results. This deviation in the results between the two methods shows that the interference inside the canceler does not have a Gaussian distribution. However, it is a good approximation to model the interference as Gaussian noise. Note that the λ factor is a proper figure of merit to compare the feedback functions with different system parameters.

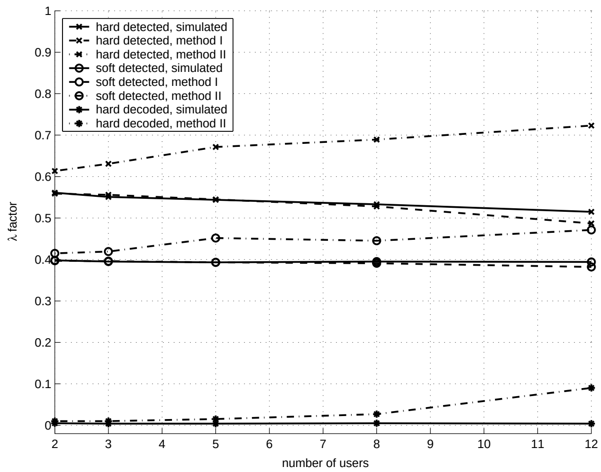

Fig. 4. λ factor at a target BER of 10^{-3} for AWGN channel.

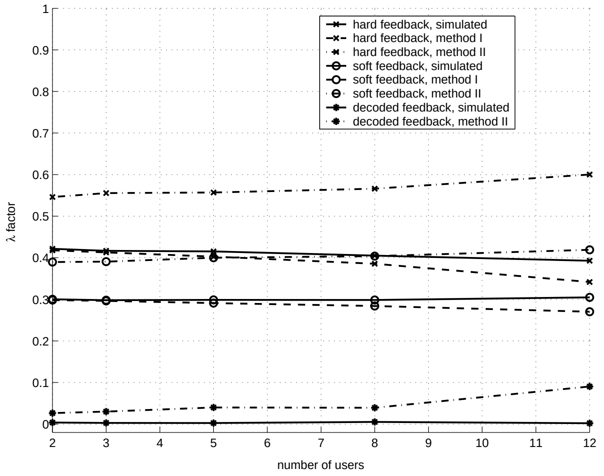

Fig. 5. λ factor at a target BER of 10^{-3} for 3 path fading channel.

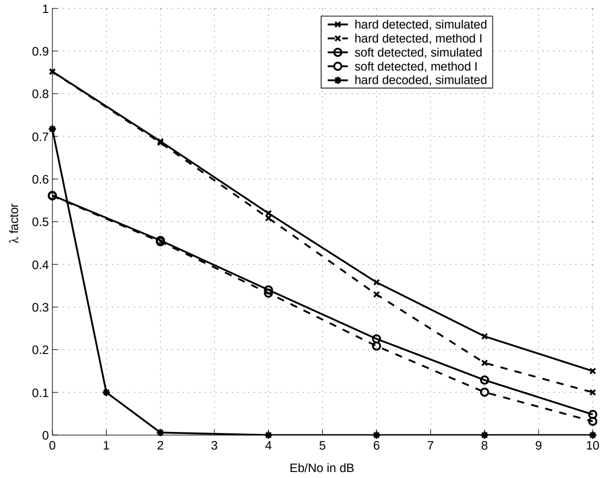

Fig. 6. λ factor with $K = 8$ users as a function of E_b/N_o for AWGN channel.

The same relative comparison results obtained from Fig. 3 can also be inferred from Fig. 4 and Fig. 5. It can be seen that the value of λ with hard decoded feedback is nearly zero which indicates that most of the interference is canceled and, therefore, the performance approaches that of a system with only one user. Moreover, for a given feedback function, the value of λ for the three path fading channel is less than that for the AWGN channel, even though the required E_b/N_o to achieve the target BER is higher for the fading channel.

Fig. 6 presents the calculated (method I) and simulated values of λ versus E_b/N_o for $K = 8$ users over an AWGN channel. It can be seen that at low SNR, SIC barely subtracts any interference due to many errors in the detection (the value of λ is very high). On the other hand, as the SNR increases, the efficiency of the SIC receiver becomes better for the different feedback functions, leading to less cancellation errors and less residual interference. Again, the results obtained using method I nearly coincide with the simulation results especially for the range of practical interest (BER between 10^{-3} and 10^{-4} which is equivalent to $2 < E_b/N_o < 6$ dB). The same relative observations have also been realized for the three path fading channel.

The derived λ values can also be used to estimate the system user capacity using SIC. For example, SIC with soft detected feedback and two cancellation stages has $\lambda \approx 0.4$ at a BER of 10^{-3} over an AWGN channel. This indicates that in a system with one cell (no intercell interference), the system user capacity using SIC is more than double the capacity using the conventional SUD receiver.

V. Conclusions

In this work, we have defined and analytically evaluated using two methods the λ factor which models the amount of residual interference remaining after applying serial interference cancellation (SIC) at the receiver of a WCDMA system. The adopted system model resembles the uplink of the WCDMA FDD mode of UMTS. Three feedback decision functions with trade–off in performance and complexity were considered. Computer link level simulation results were also done to verify the calculated results.

It is shown that SIC with $K = 12$ users and spreading factor $N_d = 8$ can achieve a gain of 3 dB to 7 dB depending on the used feedback function compared to the conventional SUD receiver for an AWGN channel. Moreover, using decoded feedback nearly perfect cancellation can be achieved ($\lambda \approx 0$), while using detected feedback λ varies between 0.4 and 0.7. This shows for example that using SIC with soft detected feedback, around 60% of the interference is canceled inside the serial interference canceler. The evaluation of the λ factor has been extended to multipath fading channels and performance results for a three path fading channel have also been presented.

Results are being extended to include the effects of non–ideal channel estimation. The worse the channel estimation, the higher is the residual interference and, thus, the higher is the value of λ.

References

[1] S. Verdú, *Multiuser Detection*. New York: Cambridge University Press, 1998.
[2] P. Patel and J. Holtzman, "Analysis of a simple successive interference cancellation scheme in DS/CDMA system," *IEEE Journal on Sel. Areas in Comm.*, vol. 12, pp. 796–807, June 1994.
[3] M. Mecking, Z. Dawy, and A. Seeger, "Enhanced receiver structure for cellular multiple–access systems with two service classes," in 4^{th} *International ITG Conference on Source and Channel Coding*, (Berlin, Germany), January 28–30 2002.
[4] Z. Dawy, S. Davidović, M. Mecking, and A. Seeger, "Feedback decision functions for WCDMA serial interference cancellation receivers with pilot–aided channel estimation," in *IEEE ISSSTA 2002*, (Prague, Czech Republic), September 2002.
[5] J. G. Andrews and T. H. Meng, "Transmit power and other–cell interference reduction vis successive interference cancellation with imperfect channel estimation," in *IEEE ICC 2001*, (Helsinki, Finland), June 2001.
[6] M. Shibahara, H. Fujji, S. Suwa, T. Saba, and I. Sasase, "Multi–stage serial interference canceller with new interference rejection weight control using residual signal at the end of each stage for DS–CDMA systems," in *ISITA 2000*, (Honolulu, Hawaii), pp. 899–902, November 2000.
[7] H. Holma and A. Toskala, *WCDMA for UMTS*. England: Wiley, 2000.
[8] M. D. Godfrey, "The TANH transformation," tech. rep., Information Systems Laboratory, Stanford University.
[9] J. G. Proakis, *Digital Communications*. New York: McGraw–Hill, 4th ed., 2001.

Top