Segregating In- and Other-Cell Interference with Applications to Decentralized Admission Control

Daniel Catrein, *Member, IEEE,* and Rudolf Mathar, *Member, IEEE*

***Abstract*—This paper deals with the intertwined problems of feasibility, power allocation and call admission control on the basis of the signal-to-interference-ratio in multi-cell CDMA networks. Positively homogeneous in-cell interference functions are introduced. Under this general concept optimum power allocations are determined by first solving in-cell interference problems with fixed background noise, and subsequently a small system of linear coupling equations. This approach simultaneously clarifies the existence of some power allocation such that minimum SIR requirements are fulfilled. The decomposition is also utilized for designing a decentralized admission control algorithm. Finally, guidelines are given on how required parameters may be estimated in existing network structures.**

***Index Terms*—Code Division Multiple Access, multi-cell interference, matched filter, successive interference cancellation, minimum mean squared error receiver, power control, dimensionality reduction.**

I. INTRODUCTION

FEASIBILITY, power control and admission control for code division multiple access (CDMA) radio networks are closely related. On one hand, the question arises whether for a given set of signal-to-interference-plus-noise thresholds there exists a power assignment such that each user's SINR meets this threshold. On the other hand, once having clarified that a solution exists, for practical purposes there is need for methods to compute the power minimal solution. In addition to that, call admission control (CAC) is essential to ensure high system performance and feasibility by adjusting the number of admitted calls to the actual interference conditions. The question in CAC is whether the network can admit an incoming user without disrupting any other connection.

In recent literature, much attention has been paid to the intertwined problems of power control, feasibility, resource allocation, and admission control for code division multiple access (CDMA) radio networks. However, most analytic research focuses on the single-cell setup treating interference from all other mobiles as noise. The existence of admissible power allocations and the geometrical shape of the feasibility and capacity region are investigated in [1]–[3]. Questions of resource allocation are addressed in [4], [5]. A general concept of algorithmic power control has been introduced in [6] and is further developed, e.g., in [7], [8]. Admission control, particularly for multimedia and variable bit rate services is considered in [9], [10], just to name a few recent articles.

The present paper utilizes analytic methods to evaluate the uplink in a multi-cell setup where interference from in-cell mobiles and other-cell stations is processed differently, and may depend on the employed receiver type. Power control in such a multi-cell network is considered in [11], [12]. There, energy efficiency is the main objective and power allocation by users is formulated as a non-cooperative game. Distributed stochastic power control algorithms in a multi-cell scenario, built upon standard interference functions from [6], are developed in [13].

An overview of existing CAC algorithms is given in [10]. Existing distributed call admission control schemes rely on local interference measurements, and often require specialized algorithms executed at the mobiles, see [14]. The scheme presented here is related to [15] in that it also utilizes standard distributed power control algorithms at the mobiles. For example, UMTS uses two different power control algorithms. The outer loop power control sets SINR target values for each mobile and the inner loop adjusts the transmit power up to 1500 times per second in order to meet this SINR target value, see, e.g., [16].

Novel contributions both to the power allocation and the call admission control problem are given in the present work. We first introduce the general concept of positively homogeneous in-cell interference functions. The interpretation is that in-cell interference scales linearly with the power vector of stations linked to the same base station.

This allows to treat the signal-to-interference-plus-noise ratio (SINR) of different receiver types, particularly the matched filter (MF), the successive interference cancellation (SIC) and the minimum mean squared error (MMSE) receiver in the large system regime under a unifying approach. In Section III, we show that determining feasibility of some vector of SINR requirements may be generally decomposed into a local in-cell interference and a small size linear coupling problem. In this way, computation of an optimum power assignment is speeded up by orders of magnitude. For the MF receiver with binary random spreading we give necessary conditions for feasibility and non-feasibility of a requirement vector in Section IV.

The general decomposition concept leads to a new decentralized admission control algorithm introduced in Section V. This algorithm extends the concepts, which we introduced in [17] for the MF receiver, to the class of receivers with positively homogeneous in-cell interference function. As an

Paper approved by K. K. Leung, the Editor for Wireless Network Access and Performance of the IEEE Communications Society. Manuscript received October 23, 2007; revised July 19, 2008 and February 1, 2009.

D. Catrein was with the Institute for Theoretical Information Technology, RWTH Aachen University, Germany when working on the results presented here. He is now with Ericsson Research, Ericsson GmbH, Herzogenrath, Germany (e-mail: daniel.catrein@ericsson.com).

R. Mathar is with the Institute for Theoretical Information Technology, RWTH Aachen University, Germany e-mail: mathar@ti.rwth-aachen.de.

This work was partially supported by the UMIC Research Center.

Digital Object Identifier 10.1109/TCOMM.2009.08.070551

0090-6778/09$25.00 © 2009 IEEE

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.

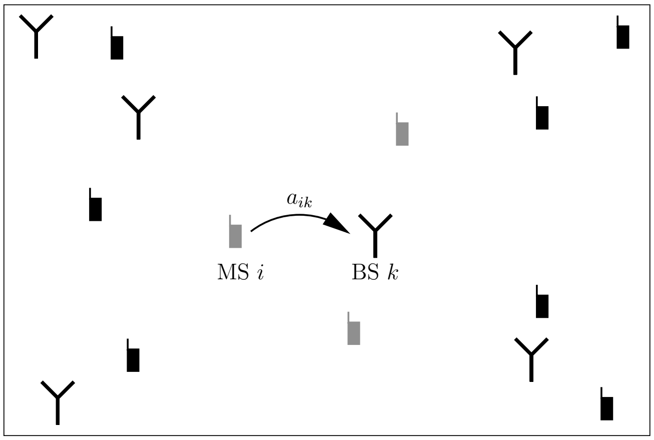


Fig. 1. In- and other-cell interference from mobiles served (gray) and mobiles not served (black) by base station k, respectively.

intermediate step, we demonstrate how the coupling solution is updated when a new user enters the system. We conclude with pointing out how required parameters may be estimated from data anyway available at each base station.

II. The Network Model

We consider the uplink of a cellular radio network consisting of mobile stations and multiple receivers as depicted in Figure 1. The network consists of K receivers or base stations labeled $1,\dots,K$ and N transmitters or mobile stations labeled $1,\dots,N$. The $N\times K$ matrix $\boldsymbol{A}=(a_{ik})_{1\le i\le N,1\le k\le K}$ denotes the channel gain from mobile station i to base station k.

We assume a fixed allocation of mobiles to base station, formalized by an assignment function

$$c:\{1,\dots,N\}\to\{1,\dots,K\}:i\mapsto k_i$$

such that k_i denotes the connecting base station of user i. The set of mobiles allocated to base station k is denoted by

$$\mathcal{C}(k)=\big\{i\in\{1,\dots,N\}\mid k_i=k\big\},\ k=1,\dots,K.$$

$\mathcal{C}(1),\dots,\mathcal{C}(K)$ forms a partition of the set $\{1,\dots,N\}$. All mobiles in $\mathcal{C}(k)$ are decoded by base station k, i.e., their signal can be subtracted from the overall signal if a successive interference cancellation receiver is used or it can be included in the calculation of the receiver vector for an MMSE receiver.

Let p_i denote the transmit power of user i and $\boldsymbol{p}=(p_1,\dots,p_N)^{\mathsf{T}}\ge 0$ the vector of transmit powers of all users in the system. We further use the notation $\boldsymbol{p}_{\mathcal{C}(k)}=(p_j)_{j\in\mathcal{C}(k)}$ to comprise the transmit power of all users connected to base station k.

The SINR of user i for a given power vector $\boldsymbol{p}$ is denoted by $\mathrm{SINR}_i(\boldsymbol{p})$. We consider receivers where $\mathrm{SINR}_i(\boldsymbol{p})$ is given by the solution of the implicit system of equations

$$\mathrm{SINR}_i=\frac{a_{ik_i}\,p_i}{I_{k_i}\big(i,\boldsymbol{p}_{\mathcal{C}(k_i)},\mathrm{SINR}_i\big)+u_i\sum_{j\notin\mathcal{C}(k_i)}a_{jk_i}\,p_j+u_i\,\tau^0_{k_i}}\tag{1}$$

for all $i=1,\dots,N$. The function

$$I_k\big(i,\boldsymbol{p}_{\mathcal{C}(k)},\mathrm{SINR}_i\big),\ i\in\mathcal{C}(k),$$

represents the interference induced by the users whose signal is decoded by the same base station k, the in-cell or local interference. As a general assumption we require that I_k is a positively homogeneous function of the power vector in cell k, precisely,

$$I_k\big(i,\kappa\,\boldsymbol{p}_{\mathcal{C}(k)},\mathrm{SINR}_i\big)=\kappa I_k\big(i,\boldsymbol{p}_{\mathcal{C}(k)},\mathrm{SINR}_i\big),\ i\in\mathcal{C}(k)$$

for all real $\kappa>0$.

The other-cell interference implied by users whose signal is not decoded by k_i is described by $\sum_{j\notin\mathcal{C}(k_i)}a_{jk_i}\,p_j$, making the reasonable assumption that the interference introduced by other users is proportional to their received power. The parameter $\tau^0_k>0$, $k=1,\dots,K$, models the background noise at receiver k. The coefficients $u_i>0$, $i=1,\dots,N$, model additional gain or attenuation of other-cell interference and background noise, respectively.

The SINR of the matched filter (MF), the successive interference cancellation (SIC) and the minimum mean squared error (MMSE) receiver fall within the scope of model (1) with a positively homogeneous in-cell interference function I_k. Because of linearity this is obvious for the MF receiver with

$$I_k^{\mathrm{MF}}\big(i,\boldsymbol{p}_{\mathcal{C}(k)},\mathrm{SINR}_i\big)=\frac{1}{L}\sum_{j\in\mathcal{C}(k)\setminus\{i\}}a_{jk}p_j,\ i\in\mathcal{C}(k),$$

and the SIC receiver where

$$I_k^{\mathrm{SIC}}\big(i,\boldsymbol{p}_{\mathcal{C}(k)},\mathrm{SINR}_i\big)=\sum_{j\in\mathcal{C}(k),j<i}\frac{\alpha_{ij}}{\alpha_{ii}}a_{jk}\,p_j+\frac{1}{L}\frac{\beta_i}{\alpha_{ii}}\sum_{j\in\mathcal{C}(k),j>i}a_{jk}\,p_j.$$

with coefficients α_{ij} and β_i determined in [18]. Positive homogeneity is also easy to demonstrate for the MMSE receiver in the large system regime introduced in [19]. Here,

$$I_k^{\mathrm{MMSE}}\big(i,\boldsymbol{p}_{\mathcal{C}(k)},\mathrm{SINR}_i\big)=\frac{1}{L}\sum_{j\in\mathcal{C}(k)\setminus\{i\}}\frac{a_{ik}\,p_i\,a_{jk}\,p_j}{a_{ik}\,p_i+\mathrm{SINR}_i\ a_{jk}\,p_j}$$

holds, which is obviously a positively homogeneous function.

III. Feasibility

A requirement vector $\boldsymbol{\gamma}=(\gamma_1,\dots,\gamma_n)$ is called feasible if there is a power allocation $\boldsymbol{p}$ such that $\mathrm{SINR}_i(\boldsymbol{p})\ge\gamma_i$ for all $i=1,\dots,N$.

It is shown in [5], [18] that for the MF, SIC, and MMSE receiver in the single cell case there exists a unique componentwise minimal power allocation $\boldsymbol{p}^*_{\mathcal{C}(k)}$ with $\mathrm{SINR}_i(\boldsymbol{p}^*_{\mathcal{C}(k)})=\gamma_i$ for all $i\in\mathcal{C}(k)$. In the present framework, this applies to the in-cell interference problems treating other-cell interference as constant background noise. Hence, solving

$$\gamma_i=\frac{a_{ik}p_i}{I_k(i,\boldsymbol{p}_{\mathcal{C}(k)},\gamma_i)+u_i\tau_k},\ i\in\mathcal{C}(k),\tag{2}$$

for some positive τ_k yields componentwise minimal solutions $\boldsymbol{p}^*_{\mathcal{C}(k)}$. Furthermore, in concert with [18], if $\boldsymbol{\gamma}^{(1)}_{\mathcal{C}(k)}=(\gamma^{(1)}_i)_{i\in\mathcal{C}(k)}$ is feasible then each $\boldsymbol{\gamma}^{(0)}_{\mathcal{C}(k)}\le\boldsymbol{\gamma}^{(1)}_{\mathcal{C}(k)}$ is feasible as well with a minimal power allocation $\boldsymbol{p}^{(0)}_{\mathcal{C}(k)}\le\boldsymbol{p}^{(1)}_{\mathcal{C}(k)}$, where "$\le$" between vectors is understood componentwise.

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.

Since $I_k(i, \boldsymbol{p}_{\mathcal{C}(k)}, \gamma_i)$ is positively homogeneous in $\boldsymbol{p}_{\mathcal{C}(k)}$ for all k a solution of (2) may be reduced to the case $\tau_k = 1$.

Proposition 1: Given requirements $\boldsymbol{\gamma}$. If there exists a solution $\boldsymbol{p}_{\mathcal{C}(k)}(1) > 0$ of

$$\gamma_i = \frac{a_{ik} p_i}{I_k(i, \boldsymbol{p}_{\mathcal{C}(k)}, \gamma_i) + u_i}, \ i \in \mathcal{C}(k), \tag{3}$$

then for any $\tau_k > 0$ the vector $\boldsymbol{p}_{\mathcal{C}(k)}(\tau_k) = \tau_k \boldsymbol{p}_{\mathcal{C}(k)}(1)$ is a solution of (2).

This means that the optimal power assignment scales linearly with the general background interference τ_k.

The main theorem now is concerned with determining a minimal global power allocation from first solving the in-cell problems and subsequently a system of linear coupling equations. Herein, $\rho(\boldsymbol{C}) = \max\{|\lambda| \mid \lambda \text{ an eigenvalue of } \boldsymbol{C}\}$ denotes the spectral radius of matrix $\boldsymbol{C}$.

Theorem 2: There exists a solution $\boldsymbol{p}^* > 0$ of

$$\gamma_i = \frac{a_{ik_i} p_i}{I_{k_i}(i, \boldsymbol{p}_{\mathcal{C}(k_i)}, \gamma_i) + u_i \sum_{j \notin \mathcal{C}(k_i)} a_{jk_i} p_j + u_i \tau_{k_i}^0}, \tag{4}$$

$i = 1, \ldots, N$, if and only if there exist solutions $\boldsymbol{p}_{\mathcal{C}(k)}(1) > 0$ of (3) for all $k = 1, \ldots, K$ and $\rho(\boldsymbol{C}) < 1$ holds, where $\boldsymbol{C} = \left(c_{km}\right)_{1 \le k,m \le K}$ is given by

$$c_{km} = \begin{cases} \sum_{j \in \mathcal{C}(m)} a_{jk} p_j(1), & \text{if } k \ne m \\ 0, & \text{if } k = m \end{cases}. \tag{5}$$

In this case, the solution $\boldsymbol{p}^*$ of (4) is given by

$$p_i^* = p_i(1) \tau_{k_i}, \ i = 1, \ldots, N,$$

where $\boldsymbol{\tau} = (\tau_1, \ldots, \tau_K)^{\mathsf{T}}$ is the unique solution of

$$(\boldsymbol{I} - \boldsymbol{C})\boldsymbol{\tau} = \boldsymbol{\tau}^0.$$

Proof: Note that $(\boldsymbol{I} - \boldsymbol{C})\boldsymbol{\tau} = \boldsymbol{\tau}^0$ equivalently reads as

$$\begin{aligned} \tau_k &= \sum_{m \ne k} c_{km} \tau_m + \tau_k^0 \\ &= \sum_{m \ne k} \tau_m \sum_{j \in \mathcal{C}(m)} a_{jk} p_j(1) + \tau_k^0 \\ &= \sum_{j \notin \mathcal{C}(k)} a_{jk} p_j(1) \tau_{k_j} + \tau_k^0 \end{aligned} \tag{6}$$

for all $k = 1, \ldots, K$. The condition $\rho(\boldsymbol{C}) < 1$ ensures that a positive solution $\boldsymbol{\tau}$ exists.

Now, assume that for each k there is a solution $\boldsymbol{p}_{\mathcal{C}(k)}(1)$ of system (3). By Proposition 1

$$\begin{aligned} \gamma_i &= \frac{a_{ik} p_i(1) \tau_{k_i}}{I_k(i, \boldsymbol{p}_{\mathcal{C}(k)}(1) \tau_{k_i}, \gamma_i) + u_i \tau_{k_i}} \\ &= \frac{a_{ik_i} p_i(1) \tau_{k_i}}{I_k(i, \boldsymbol{p}_{\mathcal{C}(k_i)}(1) \tau_{k_i}, \gamma_i) + u_i \sum_{j \notin \mathcal{C}(k_i)} a_{jk_i} p_j(1) \tau_{k_i} + u_i \tau_{k_i}^0} \end{aligned}$$

holds such that $\left(p_i(1) \tau_{k_i}\right)_{i=1,\ldots,N}$ is a solution of (4).

On the other hand, let $\boldsymbol{p}^*$ be a solution of (4). Setting

$$\tau_k = \sum_{j \notin \mathcal{C}(k)} a_{jk} p_j^* + \tau_k^0$$

gives

$$\gamma_i = \frac{a_{ik_i} p_i^* / \tau_{k_i}}{I_k(i, \boldsymbol{p}^*_{\mathcal{C}(k_i)} / \tau_{k_i}, \gamma_i) + u_i}$$

such that $\boldsymbol{p}^*_{\mathcal{C}(k)} / \tau_{k_i} = \boldsymbol{p}_{\mathcal{C}(k)}(1)$ solves (3). Furthermore,

$$\tau_k = \sum_{j \notin \mathcal{C}(k)} a_{jk} p_j(1) \tau_{k_j} + \tau_k^0$$

holds, hence by (6) the equation $(\boldsymbol{I} - \boldsymbol{C})\boldsymbol{\tau} = \boldsymbol{\tau}^0$. Vector $\boldsymbol{\tau}$ is a positive solution which implies $\rho(\boldsymbol{C}) < 1$. ■

Theorem 2 shows that the power control problem for a network of multi-user receivers may be decomposed into two parts. It also offers an elegant way to compute the optimal power allocation. First the local in-cell problems (3) are solved yielding $\boldsymbol{p}(1)$. This determines the coupling matrix $\boldsymbol{C}$. Provided that $\rho(\boldsymbol{C}) < 1$, a relatively small $K \times K$ system of linear equations $(\boldsymbol{I} - \boldsymbol{C})\boldsymbol{\tau} = \boldsymbol{\tau}^0$ is solved giving the final power allocation $\boldsymbol{p}^*$.

It also shows that a componentwise minimal solution $\boldsymbol{p}^*$ is achieved if there are componentwise minimal solutions $\boldsymbol{p}^*_{\mathcal{C}}(k)(1)$ of (3), as holds true for the three receiver types mentioned above.

IV. Optimal Power Control for the MF Receiver

Matched filter receivers with binary random spreading have a simple form of the SINR such that computations can be further elaborated. Equation (4) reads as

$$\gamma_i = \frac{a_{ik_i} p_i}{\frac{1}{L} \sum_{j \ne i} a_{jk_i} p_j + \sigma^2}, \ i = 1, \ldots, N.$$

A direct solution of this system would require solving

$$(\boldsymbol{I} - \boldsymbol{M})\boldsymbol{p} = \boldsymbol{t} \tag{7}$$

where $\boldsymbol{M} = (m_{ij})_{1 \le i,j \le N}$ is given by

$$m_{ij} = \begin{cases} \frac{L \, a_{jk_i}}{\gamma_i \, a_{ik_i}}, & \text{if } i = j \\ 0, & \text{if } i \ne j \end{cases}$$

and $\boldsymbol{t} = (\gamma_1 \, \sigma^2 / a_{1k_1}, \ldots, \gamma_N \, \sigma^2 / a_{Nk_N})^{\mathsf{T}}$. Solving (7) directly by inversion of the $N \times N$ matrix $\boldsymbol{I} - \boldsymbol{M}$ is computationally expensive, mostly even infeasible, as the number of users N in the network is generally quite high.

Using the approach of Theorem 2 reduces the computational effort drastically. Firstly, the local interference problems for $k = 1, \ldots, K$ given by

$$\gamma_i = \frac{a_{ik} \, p_i}{\frac{1}{L} \sum_{j \in \mathcal{C}(k), j \ne i} a_{jk} \, p_j + \frac{1}{L}}, \ i \in \mathcal{C}(k),$$

are considered. The solution is available in explicit form as

$$p_i(1) = \frac{1}{a_{ik} \ (1 + L/\gamma_i) \, (1 - \beta_k)}, \ i \in \mathcal{C}(k),$$

provided that

$$\beta_k = \sum_{j \in \mathcal{C}(k)} \frac{1}{1 + L/\gamma_j} < 1,$$

see [20].

Secondly, $\boldsymbol{C} = (c_{km})_{1 \le k,m \le K}$ with c_{km} given in (5) is determined. Finally, the system $(\boldsymbol{I} - \boldsymbol{C})\boldsymbol{\tau} = \boldsymbol{\tau}^0$ with $\boldsymbol{\tau}^0 = (L\sigma^2, \ldots, L\sigma^2)^{\mathsf{T}}$ is solved, yielding the solution $p_i = p_i(1)\tau_{k_i}$.

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.

TABLE I
COMPARISON OF THE RUNTIME BY DECOUPLING INTO SUBPROBLEMS AND THE TIME REQUIRED TO SOLVE (7) DIRECTLY VIA GAUSSIAN ELIMINATION. COMPUTER SYSTEM: XENON, 2.4GHZ.

Problem size		Computation time	
K	N	Decoupling	Direct solution of (7)
100	1000	0.09s	14.46s
400	1000	2.16s	14.81s
100	10000	1.13s	$>$ 4h
400	10000	4.52s	$>$ 4h
1600	10000	214.30s	$>$ 4h

If Gaussian elimination[1] is used to solve the $(K\times K)$ system of linear equations, the total computational effort is $O(NK+K^3)$, for real networks much smaller than $O(N^3)$ required for the direct approach. This is reflected by numerical experiments reported in Table I. As can be seen, for relevant problem sizes the direct approach is practically infeasible.

We conclude this session by giving simple necessary conditions for the feasibility or non-feasibility of some requirement vector $\boldsymbol{\gamma}$.

Theorem 3: Let $\zeta_1,\ldots,\zeta_K > 0$ be such that $\sum_{l\neq k_i} a_{il} \le \zeta_{k_i} a_{ik_i}$ for all $i=1,\ldots,N$. Then there exists a feasible power allocation if for all $k=1,\ldots,K$

$$\sum_{i\in\mathcal{C}(k)} \frac{1}{L/\gamma_i+1} < \frac{1}{\zeta_k+1}.$$

If, on the other hand, $\sum_{l\neq k_i} a_{il} \ge \zeta_{k_i} a_{ik_i}$ for all $i=1,\ldots,N$, then there is no feasible power allocation if for all $k=1,\ldots,K$

$$\sum_{i\in\mathcal{C}(k)} \frac{1}{L/\gamma_i+1} > \frac{1}{\zeta_k+1}.$$

Proof: Fix $m\in\{1,\ldots,K\}$, and consider the mth column sum of $\boldsymbol{C}=(c_{km})$.

$$\begin{aligned}\sum_{k\neq m} c_{km} &= \sum_{k\neq m}\sum_{j\in\mathcal{C}(m)} a_{jk}p_j(1)\\ &= \sum_{j\in\mathcal{C}(m)} \frac{1}{(L/\gamma_j+1)\left(1-\sum_{l\in\mathcal{C}(m)}\frac{1}{L/\gamma_l+1}\right)} \sum_{k\neq m}\frac{a_{jk}}{a_{jm}}\\ &\le \sum_{j\in\mathcal{C}(m)} \frac{1}{(L/\gamma_j+1)\left(1-\sum_{l\in\mathcal{C}(m)}\frac{1}{L/\gamma_l+1}\right)}\zeta_m\\ &= \zeta_m\,\frac{\sum_{l\in\mathcal{C}(m)}\frac{1}{L/\gamma_l+1}}{1-\sum_{l\in\mathcal{C}(m)}\frac{1}{L/\gamma_l+1}}\end{aligned}$$

The right hand side of this chain is less than one if and only if

$$\sum_{l\in\mathcal{C}(m)} \frac{1}{L/\gamma_l+1} < \frac{1}{\zeta_m+1}. \tag{8}$$

Hence, if (8) is satisfied for all $m=1,\ldots K$, the assertion follows from Gersgorin's theorem, ensuring that that the spectral radius satisfies $\rho(\boldsymbol{C}) \le \max_m \sum_{k\neq m} c_{km}$, see [22, p. 346]. Reverting the above inequality signs yields the second assertion along the same lines by using the inequality $\rho(\boldsymbol{C}) \ge \min_m \sum_{k\neq m} c_{km}$. ∎

[1]The minimal computational complexity for solving a system of N equations or the inversion of a general $N\times N$ matrix is still unknown. So far, the best published result for matrix inversions is $O(N^{2.376})$, see [21].

In a balanced load situation it may well be assumed that each mobile is allocated to the base station with the least attenuated path, i.e., $a_{ik} \le a_{ik_i}$ for all i,k. In this case, it follows easily from Theorem 3 that a feasible power allocation exists whenever

$$\sum_{i\in\mathcal{C}(k)} \frac{1}{L/\gamma_i+1} < \frac{1}{K} \quad \text{for all } k=1,\ldots,K.$$

V. ADMISSION CONTROL

The decomposition approach in Section III is perfectly suited for the design of decentralized admission control algorithms, as is developed in the following for receivers which comply with interference formula (1).

Cellular CDMA networks are designed not to have a central unit that collects information about all active mobiles, which immediately implies restrictions on CAC algorithms. Base stations gather only information about the local status, namely those mobiles which are linked. Hence, CAC algorithms must operate with limited information in a decentralized way.

Here, we present a method to update the power setting for all mobiles after admission of a new user. Our approach allows inclusion of individual power constraints in the admission decision. Furthermore, all information required for an admission decision can be collected at the base stations and is usually already available in existing networks for handoff purposes. The admission decision is based on measuring the total other-cell interference at each base station in a prediction phase. We show that this admission decision is optimal and that neither in the prediction phase nor after the admission of another customer any individual quality constraints are violated.

Note that the approach presented here is also applicable to the case when a user leaves the system. Feasibility is obviously ensured in this case. However, the method to predict the overall interference after admission of a user can be equivalently used to predict the overall interference after departure of a user.

A. Admission of a New User

We assume that a network supports the requirements $\boldsymbol{\gamma}=(\gamma_1,\ldots,\gamma_N)$ of N users before a new user arrives. Hence, a solution of the power control problem (4) exists for N users. Thus, the conditions of Theorem 2 hold, and the coupling matrix $\boldsymbol{C}$ fulfills $\rho(\boldsymbol{C}) < 1$. We denote the corresponding base station interference vector by

$$\boldsymbol{\tau}^{\mathrm{old}} = (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\tau}_0. \tag{9}$$

Admission of a new user $N+1$ boils down to the question if the power control problem (4) still has has a solution with this user added to the network. Equivalently, the conditions of Theorem 2 may be checked for $N+1$ users. Without loss of generality, we assume that the new user $N+1$ is assigned to base station K. The new assignment of mobiles to base stations $\tilde{\mathcal{C}}(k)$ is accordingly given by

$$\tilde{\mathcal{C}}(k) = \begin{cases}\mathcal{C}(k), & \text{if } k\neq K,\\ \mathcal{C}(k)\cup\{N+1\}, & \text{if } k=K.\end{cases} \tag{10}$$

Assume that the solution to the in-cell power control problem (3) exists for $i\in\tilde{\mathcal{C}}(K)$ with user $N+1$ included.

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.

Otherwise, no feasible power allocation exists and user $N+1$ is rejected straight away. Let $\tilde{p}_i(1)$ denote the corresponding solution of (3) for $N+1$ users. Obviously, $\tilde{p}_i(1)$ differs from $p_i(1)$ only for users $i \in \mathcal{C}(K)$. Furthermore, only local information about the mobiles connected to base station K is needed to solve the in-cell problem.

Finally, let $\tilde{\mathcal{C}} = (\tilde{c}_{km})_{1\le k,m\le K}$ denote the coupling matrix for $N+1$ users. User $N+1$ is admitted if there is positive solution $\boldsymbol{\tau}^{\text{new}}$ of

$$(\boldsymbol{I} - \tilde{\boldsymbol{C}})\boldsymbol{\tau} = \boldsymbol{\tau}^0, \tag{11}$$

where the thermal background noise vector $\boldsymbol{\tau}^0$ is assumed to be unchanged for both cases.

We aim at using the previous base station interference vector $\boldsymbol{\tau}^{\text{old}}$ to compute the unknown vector $\boldsymbol{\tau}^{\text{new}}$. According to Theorem 2 a solution to (11) exists if and only if $\rho(\tilde{\boldsymbol{C}}) < 1$.

Observe that matrices $\boldsymbol{C}$ and $\tilde{\boldsymbol{C}}$ differ only in the last column. Hence, the difference reads as

$$\boldsymbol{\Delta} = \tilde{\boldsymbol{C}} - \boldsymbol{C} = \begin{pmatrix} 0 & \cdots & 0 & \delta_1 \\ \vdots & & \vdots & \vdots \\ 0 & \cdots & 0 & \delta_K \end{pmatrix}$$

with $\delta_K = 0$ and

$$\begin{aligned} \delta_k &= \sum_{j\in\tilde{\mathcal{C}}(K)} a_{jk}\,\tilde{p}_j(1) - \sum_{j\in\mathcal{C}(K)} a_{jk}\,p_j(1) \\ &= \sum_{j\in\mathcal{C}(K)} a_{jk}\,(\tilde{p}_j(1) - p_j(1)) + a_{N+1,k}\,\tilde{p}_{N+1}(1) \\ &\ge 0, \quad k = 1,\ldots,K-1. \end{aligned}$$

Equation (11) may be written as

$$(\boldsymbol{I} - \boldsymbol{C} - \boldsymbol{\Delta})\boldsymbol{\tau} = \boldsymbol{\tau}^0. \tag{12}$$

In summary, once the local interference problem can be solved, admitting a new user only affects a single column of the coupling matrix.

Trivially, feasibility is always granted if we are interested in the situation where a users leaves the system. If this user was served by K, it is easy to see that (12) holds, however, with $\delta_k \le 0$ for all $k \in \{1,\ldots,k\}$.

In the following we develop a decentralized algorithm which leads to the admission of a new user if and only if the system of equations (12) has a positive solution.

B. A Decentralized Admission Control Algorithm

Assume that prior to accommodating a new user the system is stable, hence $\rho(\boldsymbol{C}) < 1$. Then equation (12) for the system enlarged by one more user has a solution $\boldsymbol{\tau} > 0$ if and only if

$$\big(\boldsymbol{I} - (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\Delta}\big)\boldsymbol{\tau} = (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\tau}^0. \tag{13}$$

for some positive $\boldsymbol{\tau}$. By Perron-Frobenius theory this holds true if and only if $\rho\big((\boldsymbol{I}-\boldsymbol{C})^{-1}\,\boldsymbol{\Delta}\big) < 1$.

While the above equivalence is valid for arbitrary matrices $\boldsymbol{\Delta}$, the special structure considered in the present application allows for an explicit representation of $\big(\boldsymbol{I}-(\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\Delta}\big)^{-1}$, which plays the central role for solving (13).

Proposition 4: Let $\boldsymbol{\delta} = (\delta_1,\ldots,\delta_K)'$ denote the Kth column of $\boldsymbol{\Delta}$ and

$$\boldsymbol{\lambda} = (\lambda_1,\ldots,\lambda_K)' = (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\delta}.$$

It holds that

$$\rho\big((\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\Delta}\big) = \lambda_K.$$

Furthermore, if $\lambda_K < 1$, then

$$\big(\boldsymbol{I} - (\boldsymbol{I}-\boldsymbol{C})^{-1}\,\boldsymbol{\Delta}\big)^{-1} = \boldsymbol{I} + \frac{1}{1-\lambda_K}\big(\boldsymbol{0}_{K\times K-1},\boldsymbol{\lambda}\big).$$

Proof: By the block structure of $\boldsymbol{\Delta}$ we obtain

$$(\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\Delta} = (\boldsymbol{I}-\boldsymbol{C})^{-1}(\boldsymbol{0}_{K\times K-1},\boldsymbol{\delta}) = (\boldsymbol{0}_{K\times K-1},\boldsymbol{\lambda}).$$

The only non-zero eigenvalue of this matrix is λ_K, which proves the first part. Further, as can be easily verified, the inverse of $\boldsymbol{I} - (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\Delta}$ is given by

$$\big(\boldsymbol{I} - (\boldsymbol{0}_{k\times k-1},\boldsymbol{\lambda})\big)^{-1} = \begin{pmatrix} 1 & 0 & \cdots & 0 & \frac{\lambda_1}{1-\lambda_K} \\ 0 & 1 & \cdots & 0 & \frac{\lambda_2}{1-\lambda_K} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & \frac{\lambda_{K-1}}{1-\lambda_K} \\ 0 & 0 & \cdots & 0 & \frac{1}{1-\lambda_K} \end{pmatrix}$$

With $\frac{1}{1-\lambda_K} = 1 + \frac{\lambda_k}{1-\lambda_K}$ the proof is complete. ■

For the purpose of designing an admission control algorithm we now introduce an additional parameter ε and consider the system with N users and increased background noise, namely

$$(\boldsymbol{I}-\boldsymbol{C})\boldsymbol{\tau} = \boldsymbol{\tau}^0 + \varepsilon\boldsymbol{\delta}. \tag{14}$$

Under the general assumption that $\rho(\boldsymbol{C}) < 1$ the system of equations (14) has a solution for any $\varepsilon > 0$, namely

$$\boldsymbol{\tau}^{\varepsilon} = (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\tau}^0 + \varepsilon(\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\delta} = \boldsymbol{\tau}^{\text{old}} + \varepsilon\boldsymbol{\lambda}.$$

Now, let

$$\boldsymbol{\tau}^{\boldsymbol{\Delta}} = \boldsymbol{\tau}^{\varepsilon} - \boldsymbol{\tau}^{\text{old}}$$

denote the difference. Since $(\boldsymbol{I}-\boldsymbol{C})^{-1}$ has nonnegative entries, $\boldsymbol{\tau}^{\boldsymbol{\Delta}}$ has nonnegative components as well.

Theorem 5: The system of equations (11) with one more user assigned to cell K has a solution if and only if

$$\frac{\tau_K^{\Delta}}{\varepsilon} < 1.$$

In this case, the solution $\boldsymbol{\tau}^{\text{new}}$ is obtained as

$$\boldsymbol{\tau}^{\text{new}} = \boldsymbol{\tau}^{\text{old}} + \frac{\tau_K^{\text{old}}}{\varepsilon - \tau_K^{\Delta}}\boldsymbol{\tau}^{\Delta}$$

and $\boldsymbol{\tau}^{\text{new}} \ge \boldsymbol{\tau}^{\text{old}}$ holds. Furthermore, if $\boldsymbol{C}$ is irreducible, then $\boldsymbol{\tau}^{\text{new}} > \boldsymbol{\tau}^{\text{old}}$.

Proof: Since $\lambda_K = \frac{\tau_K^{\Delta}}{\varepsilon}$, the first part is a direct consequence of (13) and Proposition 4. The second part follows from

$$\begin{aligned} \boldsymbol{\tau}^{\text{new}} &= \big(\boldsymbol{I} - (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{\Delta}\big)^{-1}\big)\boldsymbol{\tau}^{\text{old}} \\ &= \Big(\boldsymbol{I} + \frac{1}{1-\lambda_K}\big(\boldsymbol{0}_{K\times K-1},\boldsymbol{\lambda}\big)\Big)\boldsymbol{\tau}^{\text{old}} \\ &= \boldsymbol{\tau}^{\text{old}} + \frac{\tau_K^{\text{old}}}{1-\lambda_K}\boldsymbol{\lambda} \\ &= \boldsymbol{\tau}^{\text{old}} + \frac{\tau_K^{\text{old}}}{\varepsilon - \tau_K^{\Delta}}\boldsymbol{\tau}^{\Delta}. \end{aligned}$$

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.

Finally, recall that $\boldsymbol{\lambda} = (\boldsymbol{I} - \boldsymbol{C})^{-1}\boldsymbol{\delta} \geq \boldsymbol{0}$. The inverse $(\boldsymbol{I} - \boldsymbol{C})^{-1}$ is strictly positive if $\boldsymbol{C}$ is irreducible. Hence, $\boldsymbol{\lambda} > \boldsymbol{0}$ holds whenever $\boldsymbol{\delta} \neq \boldsymbol{0}$. ∎

Again, it is easy to see that $\boldsymbol{\tau}^{\text{new}}$ carries over for the situation where we are interested in the overall interference if a user leaves the system.

Power constraints play an important role in practical systems, particularly for small battery-powered handsets. Admitting a new user can only be allowed within the individual power constraints of each subscriber such that

$$p_i \leq p_i^{\max},\ i = 1, \ldots, N+1, \tag{15}$$

is required. The following theorem includes power constraints into the admission process, hence extending the previous result.

Theorem 6: Let $\boldsymbol{C}$ be irreducible and define

$$\check{\tau}_k = \min_{i \in \mathcal{C}(k)} \frac{p_i^{\max}}{p_i(1)},\ k = 1, \ldots, K,$$

and

$$\check{\varepsilon} = \min_{k:\delta_k \neq 0} \Big(\frac{\tau_k^0}{\delta_k}\Big) \cdot \min_k \Big(\frac{\check{\tau}_k - \tau_k^{\text{old}}}{\tau_k^{\text{old}}}\Big).$$

1) If $\check{\tau}_k = \tau_k^{\text{old}}$ for some k, then no new user can be admitted.
2) Let $0 < \varepsilon \leq \check{\varepsilon}$. Then (14) has a solution $\boldsymbol{\tau}^{\varepsilon} \leq \check{\boldsymbol{\tau}}$ corresponding to a feasible power allocation.
3) For any $0 < \varepsilon \leq \check{\varepsilon}$ a power allocation constrained by (15) for $N+1$ users exists if

$$\frac{\tau_K^{\Delta}}{\varepsilon} < 1 \quad \text{and} \quad \tau_k^{\text{new}} \leq \min_{i \in \tilde{\mathcal{C}}(k)} \frac{p_i^{\max}}{\tilde{p}_i(1)}$$

for all base stations $k \in \{1, \ldots, K\}$.

Proof: Recall that $p_i = \tau_{k_i} p_i(1)$ and, by Theorem 5, $\boldsymbol{\tau}^{\text{new}} > \boldsymbol{\tau}^{\text{old}}$. Hence, there is some index k such that

$$\tau_k^{\text{new}} > \check{\tau}_k = \min_{i \in \mathcal{C}(k)} \frac{p_i}{p_i(1)} \geq \min_{i \in \mathcal{C}(k)} \frac{p_i^{\max}}{\tilde{p}_i(1)}.$$

This is a contradiction to constraints (15).

To prove 2) we show that $\check{\boldsymbol{\tau}} \geq \boldsymbol{\tau}^{\varepsilon} = \boldsymbol{\tau}^{\text{old}} + \varepsilon\lambda$ which is equivalent to $\check{\boldsymbol{\tau}} - \boldsymbol{\tau}^{\text{old}} \geq \varepsilon\boldsymbol{\lambda}$. If $\boldsymbol{\delta} = 0$, the above obviously holds. Let $\boldsymbol{\delta} \neq \boldsymbol{0}$ and $\varepsilon' = \min_k \frac{\check{\tau}_k - \tau_k^{\text{old}}}{\tau_k^{\text{old}}}$. Then

$$\check{\boldsymbol{\tau}} - \boldsymbol{\tau}^{\text{old}} \geq \varepsilon' \boldsymbol{\tau}^{\text{old}} = \varepsilon'(\boldsymbol{I} - \boldsymbol{C}')^{-1}\boldsymbol{\tau}^0$$

follows. For $\varepsilon'' = \min_{k:\delta_k \neq 0} \frac{\tau_k^0}{\delta_k}$ we obtain

$$(\boldsymbol{I} - \boldsymbol{C})^{-1}\boldsymbol{\tau}^0 \geq \varepsilon''(\boldsymbol{I} - \boldsymbol{C}')^{-1}\boldsymbol{\delta} = \varepsilon''\boldsymbol{\lambda}.$$

Hence, for any $\varepsilon \leq \varepsilon'\varepsilon'' = \check{\varepsilon}$ assertion 2) follows.

Part 3) is a direct consequence of Theorem 5. ∎

Theorem 6 forms the basis for the following admission control algorithm.

Algorithm `(admission_control)`
Assume a new user $N+1$ enters a stable CDMA system with some feasible $\boldsymbol{\gamma}$ and according power allocation $\boldsymbol{p}$ for N users.

1) User $N+1$ reports its SINR requirement γ_i and the path loss values $a_{N+1,k}$ for all $k = \{1, \ldots, K\}$ to base station K.
2) Base station K requests each base station $k \in \{1, \ldots, K\}$ to determine the current other-cell interference factor τ_k^{old}. These values together with $\check{\tau}_k$ are transmitted to base station K.
3) Base station K computes $\boldsymbol{\delta}$ and $\check{\varepsilon}$. If $\check{\varepsilon} = 0$, the arriving user is rejected.
Base station K selects some $0 < \varepsilon \leq \check{\varepsilon}$ and reports to each base station k the values ε and δ_k.
4) Each base station adjusts the SINR target values for its mobile stations, as if the background noise τ_k^0 at this station rises to $\tau_k^0 + \varepsilon\,\delta_k$.
5) The distributed power control algorithm implemented in the network adjusts the powers for all users.
6) Each base station determines the new other-cell interference factor τ_k^{ε} and reports it to base station K.
7) If $\tau_K^{\Delta} \geq \varepsilon$ the new user is rejected.
Otherwise, base station K computes $\boldsymbol{\tau}^{\text{new}}$. If $\tau_K > \min_{i \in \mathcal{C}(K)} \frac{p_i^{\max}}{\tilde{p}_i}$ or $\tau_k > \check{\tau}_k$ for any $k \neq K$, the user is rejected, otherwise the user is admitted.

If $\boldsymbol{C}$ is irreducible, Theorem 6 states that algorithm `admission_control` is optimal in the sense that a user is admitted if and only if there exists a feasible power allocation subject to all power constraints. Additionally, it is assured that during the execution of steps 1 to 6 always a feasible power allocation is used. Notice that irreducibility of the matrix of channel gains and consequently of $\boldsymbol{C}$ is commonly satisfied in mobile communication networks.

If $\boldsymbol{C}$ is not irreducible the algorithm might reject a newly arriving user unnecessarily. This is the case if there is some other user transmitting with its maximum power, however not affected by the admission of a new user. In this case, rejecting the newly arriving user is reasonable as the network is already operating at the capacity limit. However, even for reducible $\boldsymbol{C}$ a user will never be wrongly accepted.

The algorithm is distributed and a limited amount of data has to be exchanged between base station K and the other base stations in each of the Steps 2), 3) and 6). Step 4) of the algorithm rests on the standard power control algorithm implemented in the network. No further communication between the mobiles is necessary.

We now briefly discuss how parameters needed by the algorithm may be collected or estimated in real networks. The total received power in the transmission band τ_k^{tot} can be easily measured at each base station $k \in \{1, \ldots, K\}$. Subtracting the interference caused by local users gives τ_k. Further, it is reasonable to assume that base station k knows the minimal SINR requirements γ_i and transmission powers p_i of all linked mobile stations $i \in \mathcal{C}(k)$. Path loss information from the mobiles to the serving and surrounding base station are also commonly available. Each mobile i measures the downlink transmission gain a_{ik}^m from its neighboring base stations for handoff purposes by analyzing their pilot signals. If the frequency used for up- and downlink are close-by, the path gains will essentially only differ in fast fading effects. Averaging the downlink channel gain a_{ik}^m at the mobiles over sufficiently many values leads to a reliable estimate $\hat{a}_{ik}$ for a_{ik}. Remaining differences are mainly due to fast fading effects. Admission control, however, will generally try to cope with fast fading effects by appropriate fading margins. An

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.

admission decision on the basis of fast fading is not desirable as the time scale of fast fading is much smaller than the average duration of a call or the average interarrival times for users.

Alternatively, the path gain can be estimated from the uplink bit error rate. Under mild assumptions the BER is a strictly monotonic function of the SINR. This knowledge of the SINR can be used to evaluate the channel gain as the overall interference τ_k^{tot} is known.

In summary, it is reasonable to assume that any base station $k = 1, \ldots, K$, has sufficient information to measure and calculate $\boldsymbol{\tau}_k$. Furthermore, all parameters needed to solve the local power control problem, i.e., to compute $\boldsymbol{p}_{\mathcal{C}(K)}(1)$ and $\boldsymbol{\delta}$ is available at base station K.

We finally show that the presented algorithm converges sufficiently fast. Fast convergence is essential for real world applications where mobile networks are subject to fast changing channel conditions. Here, convergence behavior is evaluated by a relatively simple simulation setup. Extensive simulation, including all influential factors like fading and shadowing effects and different assignment schemes of mobiles to cells, would go beyond the scope of this work and will be covered by future investigations.

In the present simulation, we assume a small network of seven hexagonal cells, one central cell and six surrounding neighbors. A base station is located in the center of each cell. N mobile terminals are randomly distributed over the cells according to a uniform distribution. We assume that the path loss between each mobile and the connecting base station is purely distance dependent with a path loss exponent $\gamma > 0$. Each mobile is assigned to, and hence decoded by the spatially closest base station. Compared to previous work, the present algorithm is capable of predicting the power levels of all users, even if base stations apply advanced multi-user receivers. Hence, SIC receivers are employed at all base stations with a purely random decoding order of users.

Figure 2 exemplarily depicts the convergence behavior in step 5 of the admission control algorithm. Obviously, the predicted other-cell interference converges after only a few steps of the distributed power control algorithm towards the value that will be observed once the new user is admitted. We observed the same behavior for numerous other parameter constellations and different numbers of users. The conclusion is that the algorithm converges sufficiently fast, particularly concerning applications for UMTS where power is updated 1500 times per second.

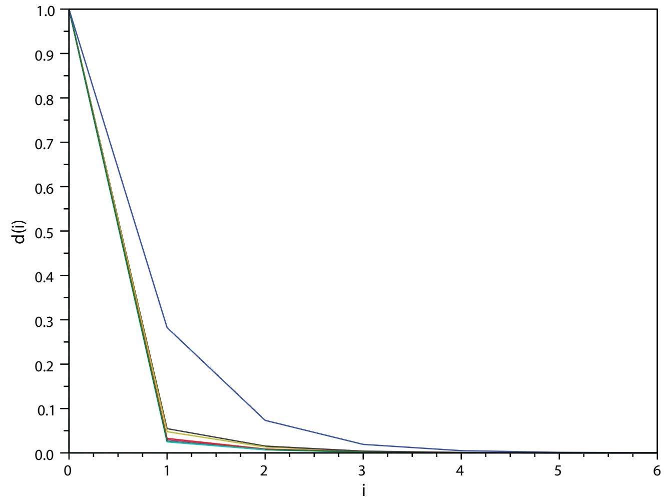


Fig. 2. Relative difference diff(i, k) between predicted other cell interference $\tau_k(i)$ after iteration i and the exact value τ_k^{new} for each cell $k \in \{1, \ldots, K\}$, i.e., $d(i) = (\tau_k^{\text{new}} - \tau_k(i))/(\tau_k^{\text{new}} - \tau_k^{\text{old}})$. The top blue line represents the central cell, i.e., where the newly arriving user should be admitted. The other six lines correspond to the surrounding cells. System parameters are typical for UMTS: 350(+1) voice users with 12.2 Kbps data rate and target SINR of 4 dB; chip rate 3.84 Mcps; noise power of -105 dBm.

VI. CONCLUSIONS

The general concept of positively homogeneous in-cell interference functions introduced in this paper allows for treating the SINR of different receiver types in CDMA under a unifying concept. We have illustrated how feasibility and the power control problem can be decomposed into in-cell interference problems and a system of coupling equations. We have demonstrated that this approach leads to a reduction of computing time by orders of magnitude. Furthermore, a decentralized call admission control algorithm has been devised which by the decomposition principle uses only parameters locally available at each base station. It works for any receiver type, even different ones between cells, as long as the in-cell interference function is positively homogeneous. In summary, contributions to the interference structure of multi-cell, multi-user CDMA systems have been achieved which lead to an implementable decentralized admission control algorithm.

REFERENCES

[1] D. Catrein, L. Imhof, and R. Mathar, “Power control, capacity, and duality of up- and downlink in cellular CDMA radio," *IEEE Trans. Commun.*, vol. 52, no. 10, pp. 1777-1785, Oct. 2004.

[2] L. A. Imhof and R. Mathar, “The geometry of the capacity region for CDMA systems with general power constraints," *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2040-2044, Sept. 2005.

[3] H. Boche and S. Stanczak, “Log-convexity of the minimum total power in cdma systems with certain quality-of-service guaranteed," *IEEE Trans. Inform. Theory*, vol. 51, no. 1, pp. 374-381, Jan. 2005.

[4] S. Stanczak, M. Wiczanowski, and H. Boche, *Resource Allocation in Wireless Networks*. Berlin: Springer, 2006.

[5] A. Feiten and R. Mathar, “Proportional QoS adjustment for achieving feasible power allocation in CDMA systems," *IEEE Trans. Commun.*, vol. 56, no. 2, pp. 254-259, Feb. 2008.

[6] R. D. Yates, “A framework for uplink power control in cellular radio systems," *IEEE J. Select. Areas Commun.*, vol. 13, no. 7, pp. 1341-1347, Sept. 1995.

[7] S. Stanczak, M. Wiczanowski, and H. Boche, “Distributed power control for optimizing a weighted sum of link-layer QoS requirements," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM 2005)*, St Louis, USA, 2005, pp. 3539-3543.

[8] S. Buzzi and H. V. Poor, “Power control algorithms for CDMA networks based on large system analysis," in *Proc. International Symp. Inform. Theory (ISIT2007)*, Nice, France, June 2007, pp. 2426-2430.

[9] D. Ayyagari and A. Ephremides, “Optimal admission control in cellular DS-CDMA systems with multimedia traffic," *IEEE Trans. Wireless Commun.*, vol. 2, no. 1, pp. 195-202, Jan. 2003.

[10] R. M. Rao, C. Comaniciu, T. V. Lakshman, and H. V. Poor, “An overview of CAC principles in DS-CDMA networks - call admission control in wireless multimedia networks," *IEEE Signal Processing Mag.*, vol. 21, no. 5, pp. 51-58, Sept. 2004.

[11] C. Saraydar, N. Mandayam, and D. Goodman, “Pricing and power control in a multicell wireless data network," *IEEE J. Select. Areas Commun.*, vol. 19, no. 10, pp. 1883-1892, Oct. 2001.

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.

[12] F. Meshkati, H. Poor, S. Schwartz, and N. Mandayam, “An energy-efficient approach to power control and receiver design in wireless data networks," *IEEE Trans. Commun.*, vol. 11, no. 11, pp. 1885-1894, Nov. 2005.

[13] J. Luo, S. Ulukus, and A. Ephremides, “Standard and quasi-standard stochastic power control algorithms," *IEEE Trans. Inform. Theory*, vol. 51, no. 17, pp. 2612-2624, July 2005.

[14] N. Bambos, S. C. Chen, and G. J. Pottie, “Channel access algorithms with active link protection for wireless communication networks with power control," *IEEE/ACM Trans. Networking*, vol. 8, no. 5, pp. 583-597, Oct. 2000.

[15] M. X. Xiao, N. B. Shroff, and E. K. P. Chong, “Distributed admission control for power-controlled cellular wireless systems," *IEEE/ACM Trans. Netw.*, vol. 9, no. 6, pp. 790-800, Dec. 2001.

[16] B. Hashem, *Wireless Communications Systems and Networks*. New York: Plenum Press, 2004, ch. Power Control Implementation in 3rd Generation CDMA Systems, pp. 157-177.

[17] D. Catrein and R. Mathar, “A capacity utilizing distributed call admission control scheme for CDMA with power constraints," in *Proc. IEEE 64st Veh. Technol. Conf. (VTC2006-Fall)*, Montreal, Canada, Sept. 2006.

[18] ——, “Feasibility and power control for linear multiuser receivers in CDMA networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4700-4709, Nov. 2008.

[19] D. N. C. Tse and S. V. Hanly, “Linear multiuser receivers: effective interference, effective bandwidth and user capacity," *IEEE Trans. Inform. Theory*, vol. 45, no. 2, pp. 641-657, 1999.

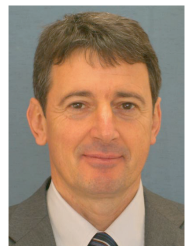
[20] R. Mathar and M. Remiche, “On the capacity of UMTS with directional antennas," in *Proc. 10th Aachen Symp. Signal Theory*, Aachen, Germany, Sept. 2001, pp. 71-75.

[21] D. Coppersmith and S. Winograd, “Matrix multiplication via arithmetic progressions," *J. Symbolic Computation*, vol. 9, no. 3, pp. 251-280, 1990.

[22] R. Horn and C. Johnson, *Matrix Analysis*. Cambridge, UK: Cambridge University Press, 1985.

Daniel Catrein received his Diploma degree in physics and his Ph.D. degree in electrical engineering and communication technology from RWTH Aachen University, Aachen, Germany, in 2001 and 2007, respectively.

From October to December 2005 he was a visiting researcher with the Department of Computer Science, ETH Zurich, Switzerland. In 2007 he was with the German Federal Office for Information Security (BSI), Bonn, Germany. He received the Gertraude-Holste best dissertation award in 2008. He is currently a Senior Research Engineer with Ericsson Research, Ericsson, Herzogenrath, Germany. His research interests include capacity estimation, resource allocation and access control for mobile communication systems. Recently, he focuses more on security aspects in wireless communication and in the distribution of multimedia content.



Rudolf Mathar received his Diploma and Ph.D. degree in mathematics from RWTH Aachen University in 1978 and 1981, respectively. Previous positions include a research fellowship at Augsburg University and a lecturer position at the European Business School. In 1989, he joined the Faculty of Natural Sciences at RWTH Aachen as a Professor of Stochastics and Computer Science. He has held the International IBM Chair in Computer Science at Brussels Free University in 1999. In spring 2001 and 2008, he was invited as Erskine Fellow to Canterbury University, Christchurch, New Zealand. In 2002, he was the recipient of the Vodafone D2 Innovation Award. In 2004 he was appointed head of the Institute of Theoretical Information Technology in the Faculty of Electrical Engineering and Information Technology at RWTH Aachen University. His research interests include mobile communication systems, particularly optimization, resource allocation and access control, as well as radio network information theory.

Authorized licensed use limited to: RWTH AACHEN. Downloaded on September 30, 2009 at 18:41 from IEEE Xplore. Restrictions apply.