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Cross-Layer QoS Management in Scheduled Multi-User Systems

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***Abstract*—Through the joint optimization of *physical* (PHY) and *media access control* (MAC) layer instances, the transmit power, that is necessary to serve given user requirements on throughput and delay, can be minimized. This article shows, how top-down cross-layer optimization can be extended to scheduled multi-user systems, by formulating analytical expressions for the relevant *quality of service* (QoS) parameters in systems with *round robin* (RRS), *maximum throughput* (MTS), and *proportional fair scheduling* (PFS). Based on this stochastic description, the power optimal mode of operation and the minimum transmit powers can be determined providing low complexity means for QoS management, that can be employed to maximize the system capacity.**

I. INTRODUCTION

Layered system architecture has served well in breaking down the design complexity of mobile communication systems like the *high speed downlink packet access* (HSDPA) [1] extension to UMTS. However, the variety and the demands of future wireless services are hard to realize with this clearly sub-optimal approach. Cross-layer optimization has evolved as one possible mean to overcome that problem by jointly optimizing the functionalities of several layers. In this contribution, we aim at the mode optimization of all layers below and including the multi-user scheduler of an HSDPA system. Objective within is the minimization of transmit power, which can be employed to maximize the number of schedulable users.

Basing on a frequency selective block Rayleigh fading channel model we derive a stochastic description of the channel energy collected by maximum ratio combining rake receiving CDMA mobile stations. Employing long scrambling codes, the multi-stream transmission over time dispersive CDMA channels can be described by an equivalent *discrete memoryless channel* (DMC), allowing the deployment of cutoff-rate based models for the system's *forward error correcting* (FEC) code. In combination with *signal to interference and noise ratio* (SINR) based descriptions of the ARQ chase combining mode, the probability $f_m[m]$, that it takes m ARQ transmissions to receive a packet error free can be computed.

Assuming equal noise power at the different *mobile stations* (MS), the regarded scheduling schemes can base on the receive signal strength and thus on the channel energy. With the stochastic means to describe the latter, the scheduling probability for all users can be assessed and the probability $f_n[n]$ of waiting n *transmission time intervals* (TTI) for the successful transmission of a packet can be determined. Note, that this probability through the mode of operation directly determines the QoS parameters throughput, i.e. the mean net data rate, and outage delay, which is defined as the time that with probability $(1-\pi_{\text{out}})$ suffices to successfully transmit a data packet.

Allowing for a preliminary assumption $\hat{p}_{\text{co}}$ on the channel outage probability, the derived system model can be inverted through a proper problem partitioning, yielding a table based mode optimization scheme, that ensures the requested QoS with minimum transmit power, i.e. with minimum SINR requirement to the single link. As both, the mode of operation and the resulting transmit power depend on the made assumption about the resulting channel outage probability p_{co}, this assumption has to be adapted in an iterative proceeding. As the underlying iteration can be proven to be contractive and the channel outage probability obviously is bound to the interval $[0;1]$, the iteration is known to converge.

Thus, with the presented techniques to include multi-user scheduling to power minimal mode optimization, means are available to efficiently manage QoS in multi-user systems, providing a significantly simplified capacity optimal interface to upper layers in the protocol stack. Moreover, the resource optimal serving of user demands allows the additional scheduling of users in the code domain of the investigated DS-CDMA systems, yielding large capacity enhancements in terms of servable user numbers.

II. SYSTEM MODEL

This section constructs analytical models for the kth users QoS parameters throughput R_k and delay τ_k depending on the mode of operation $\mathcal{M}$ consisting of the employed modulation alphabet $\mathcal{A}_k$, the FEC code rate $R_{\text{c},k}$ and the number of employed CDMA code channels c_k. Note, that R_k as well as τ_k are characteristics of underlying stochastic variables, whose random nature is caused by the complex Gaussian receive noise and the fading process on the physical channel. Thus, a first section will elaborate on some properties of block Rayleigh fading channels.

A. Channel Model

Without loss of generality, all users are assumed to face channels with Q paths, each separated by one chip duration $1/R_\chi$. The complex fading coefficients $h_{k,q}$, $q=1,\ldots,Q$ of these paths are distributed with a stationary zero mean complex

Gaussian PDF of variance $\sigma_{k,q}^2$ and are assumed independent among paths and users. Preparing the SINR based model in Section II-A, the PDF of the squared sum of these coefficients $r_k = \sum_{q=1}^{Q} |h_{k,q}|^2$ is given as:

$$f_{r_k}(r_k) = \sum_{q=1}^{Q} \alpha_{k,q} \exp\left(-\frac{r_k}{2\sigma_{k,q}^2}\right), \tag{1}$$

$$\text{with} \quad \alpha_{k,q} = \frac{\left(\sigma_{k,q}^{Q-1}\right)^2}{2\left(\prod_{\substack{f=1\\ f\neq q}}^{Q}\left(\sigma_{k,q}^2 - \sigma_{k,f}^2\right)\right)}. \tag{2}$$

The derivation of this result includes the formulation of r_k as a quadratic form in unit variance random variables, whose PDF can be determined with a method proposed in [2]. A compact proof as well as alternative expressions can be found in [3]. Note, that the CDF of (1) can be obtained analytically and the first order moment is given as:

$$\mathrm{E}[r_k] = \int_0^\infty x f_{r_k}(x)\mathrm{d}x = \sum_{q=1}^{Q} \alpha_{k,q} 4\sigma_{k,q}^4. \tag{3}$$

B. Single User Model

The use of long scrambling codes results in virtually time variant spreading codes, which allows to express the receive SINR through the orthogonality factor ν, that normalizes the interference power to the channel energy and in good approximation can be assumed constant [4], [5]. Transmitting c_k data streams in code division multiplex the SINR for a single user can be written as:

$$\gamma_k = \frac{\chi r_k \frac{1}{c_k} P_k}{(1-\nu) r_k P_k + P_{\eta,k}}, \tag{4}$$

which includes the receive power per stream with a spreading gain χ and the transmit power P_k of user k in the numerator. The denominator introduces the noise power $P_{\eta,k}$ and the interference through all streams. Assuming perfect power control techniques (cf. (20)) the channel can be modeled as a DMC with constant SINR γ_k and corresponding channel outage probability p_{co} which is given as the probability, that r_k is smaller than a critical value:

$$r_{\mathrm{crit},k} = \frac{\gamma_k P_\eta}{\left(\frac{\chi}{c_k} - \gamma_k(1-\nu)\right) P_{\max}},$$

where $P_{\max}$ is the maximum available transmit power. Neglecting the enhancement of $f_{r_k}(r_k)$ due to MTS or PFS selection of favorable channel realizations,[1] the channel outage can be obtained through the CDF of r_k as:

$$p_{\mathrm{co}} = \int_0^{r_{\mathrm{crit},1}} f_{r_k}(x)\mathrm{d}x = F_{r_k}(r_{\mathrm{crit},k}). \tag{5}$$

For this channel model the cutoff rate theorem [6], [7], [8] provides a bound on the packet error probability of a block code with block length B, modulation alphabet $\mathcal{A}_k = \{a_1, \ldots, a_q\}$ of cardinality q and binary code rate $R_{\mathrm{b}} = R_{\mathrm{c},k}\mathrm{ld}q \leq R_0(\gamma_k)$ by:

$$p_{\mathrm{PE}} \leq 2^{-B(R_0(\gamma_k)-R_{\mathrm{b}})}. \tag{6}$$

The cutoff rate $R_0(\gamma_k)$ denotes the maximum of the Gallager error exponent and for the given setting can be computed along:

$$R_0(\gamma_k) = \mathrm{ld}\,[q] - \mathrm{ld}\left[1 + \frac{2}{q}\sum_{m=1}^{q-1}\sum_{l=m+1}^{q} \mathrm{e}^{\left(-\frac{1}{4}|a_l - a_m|^2 \gamma_k\right)}\right].$$

For residual error correction we assume an ARQ protocol in the MAC layer providing the means to acknowledge the successful transmission of a packet or to demand the retransmission of lost packets. The soft combining of multiply received packets along [9], [10] and [11] can be modeled by a cumulative SINR enhancement ${}_\Delta\gamma_k[m]$ yielding the packet error probability through an extension of (6) as:

$$p_{\mathrm{PE}}[m] = 2^{-B(R_0(\gamma_k * {}_\Delta\gamma_k[m]) - R_{\mathrm{b}})}. \tag{7}$$

As mentioned above the relevant QoS parameters in single-user systems are direct functions of the probability $f_m[m]$ of waiting m ARQ attempts for the successful transmission of a packet. With (7) we derived the means to express this probability, as the product of the probabilities for loosing the first $(m-1)$ packets and succeeding in the mth attempt:

$$f_m[m] = \left(\prod_{m'=1}^{m-1} p_B[m']\right)(1 - p_B[m]). \tag{8}$$

C. Scheduling Model

Aiming at the expression of throughput and delay in multi-user systems, this section derives the probability of waiting n TTIs for the successful transmission of a packet, based upon the result in (8). To this end the three most prominent time domain scheduling algorithms are considered and investigated.

1) Round Robin Scheduling: Scheduling the K users cyclically, the RRS is independent of the instantaneous channel realization. The probability of being scheduled to a TTI with feasible channel reads:

$$p_s = \frac{1 - p_{\mathrm{co}}}{K}. \tag{9}$$

The scheduling probability p_s allows to formulate the probability of waiting exactly n TTIs for the successful transmission of a packet, conditioned on the number of ARQ repeats m as:

$$f_{n|m}[n] = (1 - p_s)^{(n-mN)} p_s^m Q_m[n]\, u[n - mN]. \tag{10}$$

Within, $u[n]$ masks the $\mathbb{R}^-$ and N denotes the number of TTIs necessary to prepare a packet for transmission. As a total of mN TTIs is spent on preparing the m transmissions, the above expression includes the probability for not being scheduled

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[1] Including this effect is straight forward by replacing $f_{r_k}(r_k)$ in (5).

$n - mN$ times, the probability for being scheduled m times, and the binomial coefficient:

$$Q_m[n] = \binom{n - mN}{m - 1}, \tag{11}$$

denoting the number of possible settings to distribute $m - 1$ scheduling events among $n - mN$ TTIs. With (8) this provides the means to formulate the probability of waiting n TTIs for the successful transmission of a packet as:

$$f_n[n] = \sum_{m=1}^{\infty} f_m[m] f_{n|m}[n]. \tag{12}$$

2) Maximum Throughput Scheduling: With (1) it is advantageous to formulate the MTS algorithm as a condition on r_k. Thus, the algorithm always schedules the user k, such that:

$$r_k > r_l,\ \forall l \neq k.$$

The probability of being scheduled therefore results from the distribution of r_k as:

$$\begin{aligned} p_\mathrm{s} =& (1 - p_\mathrm{co}) \int_0^{\infty} f_{r_k}(x) \left(\prod_{\substack{l=1 \\ l \neq k}}^{K} \left(\int_0^{x} f_{r_l}(y)\, \mathrm{d}y \right) \right) \mathrm{d}x, \\ =& (1 - p_\mathrm{co}) \int_0^{\infty} f_{r_k}(x) \left(\prod_{\substack{l=1 \\ l \neq k}}^{K} (F_{r_k}(x)) \right) \mathrm{d}x. \end{aligned} \tag{13}$$

Note, that the cumulative distribution $F_{r_k}(r_k)$ can be obtained analytically from (1), allowing the computation of p_s through the fast converging numerical quadrature of the integral in (13). With this adapted scheduling probability, the remainder of Section II-C.1 can be adopted directly allowing the computation of $f_n[n]$ through (10) and (12) with p_s from (13).

3) Proportional Fair Scheduling: Sustaining the idea of multi-user diversity while introducing a certain fairness measure, PFS schedules the user k with:

$$r_k \left(1 - \bar{\phi}_k \left(1 - \frac{1}{\mathrm{E}[r_k]}\right)\right) > r_l \left(1 - \bar{\phi}_l \left(1 - \frac{1}{\mathrm{E}[r_l]}\right)\right),$$

for all $l \neq k$. With the formulation of $\mathrm{E}[r_l]$ from (3) the above rule can be transformed into a more comfortable notation using:

$$\phi_k = 1 - \bar{\phi}_k \left(1 - \frac{1}{\sum_{q=1}^{Q} \alpha_{k,q} 4 \sigma_{k,q}^4}\right).$$

To adopt the derivations from the MTS section, let us derive the scheduling probability for this scheduling approach. Through the inversion of $r'_k = \phi_k r_k$ it can be obtained as:

$$\begin{aligned} p_s &= (1 - p_\mathrm{co}) \int_0^{\infty} \frac{1}{\phi_k} f_{r_k}\left(\frac{x}{\phi_k}\right) \prod_{\substack{l=1 \\ l \neq k}}^{K} \left(\int_0^{x} \frac{1}{\phi_l} f_{r_l}\left(\frac{y}{\phi_l}\right) dy \right) dx \\ &= (1 - p_\mathrm{co}) \int_0^{\infty} \frac{1}{\phi_k} f_{r_k}\left(\frac{x}{\phi_k}\right) \prod_{\substack{l=1 \\ l \neq k}}^{K} \left(F_{r_l}\left(\frac{y}{\phi_l}\right) \right) dx. \end{aligned}$$

With this adapted scheduling probability, the remainder of Section II-C.1 can be adopted directly allowing the computation of $f_n[n]$ through (10) and (12) with the adapted p_s.

4) Quality of Service: The formulation of the probability $f_n[n]$ allows to express the QoS parameters throughput and outage-delay in such scheduled multi-user systems. With a spreading factor χ and a chip rate R_χ the throughput can be formulated as:

$$R_k = c_k \frac{R_\chi}{\chi} R_\mathrm{b} p_\mathrm{s} \left(\left(\sum_{m=1}^{\infty} m \left(f_m[m] \right) \right)^{-1} \right). \tag{14}$$

Defining τ_k as the time, that with a probability of $1 - \pi_\mathrm{out}$ suffices to transmit a packet error-free, the outage-delay can be computed via the CDF corresponding to $f_n[n]$ through:

$$\begin{aligned} n^* &= \underset{n}{\mathrm{argmin}}\ n, \quad \text{s.t.} \quad F_n[n] \geq 1 - \pi_\mathrm{out}, \\ \tau &= n^* T_\mathrm{TTI}. \end{aligned} \tag{15}$$

III. TOP-DOWN CROSS-LAYER OPTIMIZATION

The derived analytical system model allows to minimize the necessary transmit power by selecting the optimal mode of operation for each user:

$$\mathcal{M}_k = \underset{\mathcal{M}_k}{\mathrm{argmin}}\, P_k, \quad \text{s.t.:} \begin{cases} \tau_k \leq \tau_{\mathrm{rq},k}, \\ R_k \geq R_{\mathrm{rq},k}. \end{cases} \tag{16}$$

A. Equivalent Requirements

Key approach within this optimization is to reduce (16) to a constant channel single-user problem. Allowing for a preliminary assumption $\hat{p}_\mathrm{co}$ on p_co, equivalent single-user requirements can be computed, such that realizing them in a single time-slot system will inherently assure the requirements on R and τ in a scheduled multi-user system. In general, these equivalent requirements have to fulfill the following relations:

$$\begin{aligned} \tilde{R}_{\mathrm{rq},} &= \frac{1}{p_\mathrm{s}} R_\mathrm{rq}, \\ \tilde{\tau}_\mathrm{rq} &= T_\mathrm{TTI} \sum_{i=1}^{m^*} N_i, \quad \text{with} \quad F_m[m^*] \geq 1 - \pi_\mathrm{out}. \end{aligned}$$

It is important to note, that for relevant system configurations the waterfall regions in (7) due to their steepness and due to ${}_\Delta\gamma_k$ for different protocol transmissions m are sufficiently distinct. The function $f_m[m]$ thus in a very good approximation can generally be modeled with:

$$\tilde{f}_m[m] = \begin{cases} 1 & \text{for } m = m^*, \\ 0 & \text{else}, \end{cases} \tag{17}$$

which obviously fulfills $\tilde{F}_m[m^*] \geq 1 - \pi_\mathrm{out}$ if and only if $m \geq m^*$. With this simplification, the problem reduces to finding the adequate value for m^*, that can be obtained through an iterative testing of $f_{n|m}[n]$ as (12) reduces to $f_n[n] = f_{n|m^*}[n]$.

B. Mode Optimization

Through the made assumption on p_{co} is becomes possible to directly invert the scheduling model and thus reduce the cross-layer optimization to a single-user problem. Relying on the knowledge of how to solve the downlink power control problem [12], [13], the problem furthermore can be made channel independent:

$$\mathcal{M}_k = \underset{\mathcal{M}_k}{\operatorname{argmin}}\, \gamma_k, \quad \text{s.t.:} \begin{cases} \tilde{\tau}_k \leq \tilde{\tau}_{\mathrm{rq},k}, \\ \tilde{R}_k \geq \tilde{R}_{\mathrm{rq},k}. \end{cases} \tag{18}$$

The solution thus can be obtained through an offline generated look-up table [14]. Sampling the derived system model for a finite set of possible system modes in the SINR domain provides the relation of equivalent QoS parameters and necessary receive SINR. Thus, recording the SINR minimal mode for a sufficiently close mesh in $[\tilde{\tau}_k, \tilde{R}_k]$ prior to operation suffices to solve (18) through a single table look-up. Moreover, the minimal SINR value i.e. the solution of:

$$\gamma_{\mathrm{rq},k} = \min_{\mathcal{M}_k} \gamma_k, \quad \text{s.t.:} \begin{cases} \tilde{\tau}_k \leq \tilde{\tau}_{\mathrm{rq},k}, \\ \tilde{R}_k \geq \tilde{R}_{\mathrm{rq},k}, \end{cases}, \tag{19}$$

defines the necessary transmit power P_k directly through the inversion of (4):

$$P_k = \frac{\gamma_{\mathrm{rq},k}}{\frac{\chi r_k}{c_k} - (1-\nu)\gamma_{\mathrm{rq},k} r_k} P_{\eta,k}. \tag{20}$$

C. Iterative Detection of Channel Outage

As the mode optimization and through the resulting SINR demand the downlink power control problem as well depend on the probability p_{co} of feasible channel realizations, the preliminary made assumption $\hat{p}_{\mathrm{co}}$ has to be verified and possibly adapted. Thus, this section derives an iterative proceeding to jointly determine the optimum mode and the resulting channel outage probability. With the means to determine the channel outage after the mode optimization, the joint computation of channel outage and optimum mode can be achieved through the following iterative program:

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• Initialize $\hat{p}_{\mathrm{co}}[0] = 0$.
• While $\hat{p}_{\mathrm{co}}[i] - p_{\mathrm{co}}[i] > \varepsilon$
    – Set $\hat{p}_{\mathrm{co}}[i+1] = p_{\mathrm{co}}[i]$.
    – Compute $\tilde{R}_{\mathrm{rq},}$, $\tilde{\tau}_{\mathrm{rq}}$, and $\gamma_k$.
    – Compute $p_{\mathrm{co}}[i+1]$ through (5).
• Solve (20) for positive $P_k$.
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Note, that due to the mentioned monotonicity of the mapping $\gamma_k \mapsto \left[\tilde{\tau}_k, \tilde{R}_k\right]$, $\hat{p}_{\mathrm{co}}[0] = 0$ will ensure a monotonic increase of $p_{\mathrm{co}}[i]$ with i. The proof of convergence thus is provided by the bounded nature of the probability integral in (5). Implementations show an extremely fast convergence of the above scheme, completing the power optimal mode detection in multi-user system.

IV. EVALUATION

On the background of an HSDPA [1] like system, the above concepts in the following evaluations show their applicability as well as their potentials for performance increases. The underlying environment simulates 1000 longterm settings, each consisting of 5000 TTIs. From a uniform distribution of users in the cell the Hata pathloss model:

$$\sigma^2_{k,q} = \begin{cases} -(133.3 + 33.8\log_{10}(d) + 23)\,\mathrm{dB} & \text{indoor}, \\ -(133.3 + 33.8\log_{10}(d) + 8)\,\mathrm{dB} & \text{outdoor}, \end{cases}$$

as presented in [15] and referenced in [16] together with a exponential power delay profile allows to determine the variances $\sigma^2_{k,q}$ and thus the distribution of r_k. According to this distribution, channels are generated randomly for every TTI within a longterm setting and scheduling, protocol and FEC mechanisms are simulated. The numerical values for the used system are collected in Tab. I. Assuming a noise floor of -95 dBm and a fixed antenna gain of 18 dBi, the maximum transmit power results in a maximum *effective isotropic radiated power* (EIRP) of 60 dBm.

χ	ν	N	$\Delta\gamma[m]$	π_{out}	CQI	$P_{\max}$
16	0.05	10	m	0.01	[1 – 30]	16 W

TABLE I

Demonstrating the QoS compliance of the proposed cross-layer scheme Fig. 1 shows the throughput records of three users, demanding 200 kbps, 500 kbps and 1 Mbps, respectively, for 1000 longterm settings, each resulting in a single throughput value for each user. The lines in Fig. 1 plot histograms of these records[2], revealing the superb match of requirement and measurement. The built system model allows the algorithm to precisely control the QoS parameters enabling the power minimization evaluated below. Note how neglecting the enhanced channel statistic results in over-satisfaction of the third throughput requirement.

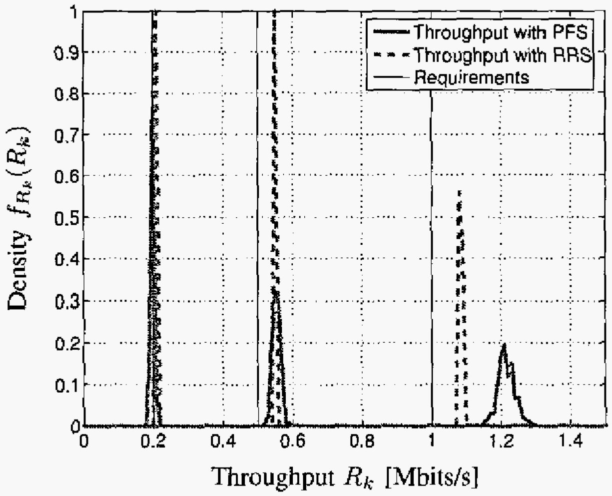

Fig. 1. QoS Compliance of the proposed solution

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[2] MTS in the vast majority of settings is not capable of serving more than one user QoS compliantly.

As Fig. 2 reveals, the QoS compliant serving of the users can be achieved with significantly less than the full available transmit power. Plotting the cumulative distribution of necessary EIRPs over the same set of longterm realizations as above, Fig. 2 compares the optimized schemes with the full-power reference as well as with a system, that selects the third best mode instead of the optimum one.

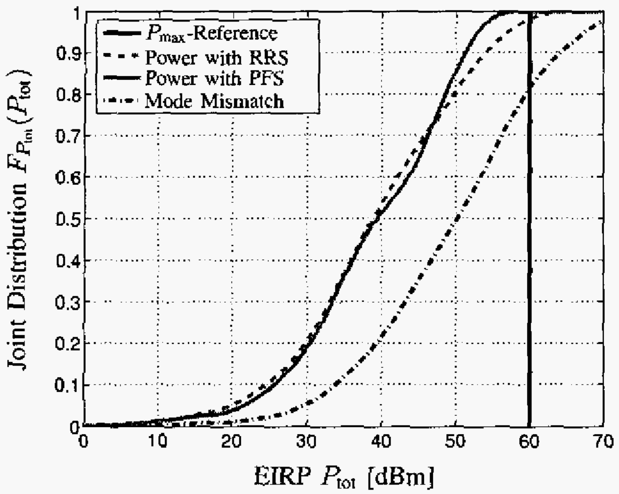

Fig. 2. Power Savings over all users

As savings in transmit power are not of direct economical use, Fig. 3 employed *cross-layer assisted resource allocation* (XARA) methods in *time domain* (TD) or in combined *time and code domain* (TCD) [17] to serve additional users with the spare transmit power. Visualizing the probability of serving K or more users, the graphs show the enormous potential, cross-layer techniques have to HSDPA scheduling units. While the chance of serving more than 4 users in the given setting with MTS and PFS only is 3% and 15% respectively, the presented optimization enables XARA schemes to achieve the same system load in 30% of all cases if only operating in the time domain, or even in 70% if additionally granted access to the unused CDMA code channels.

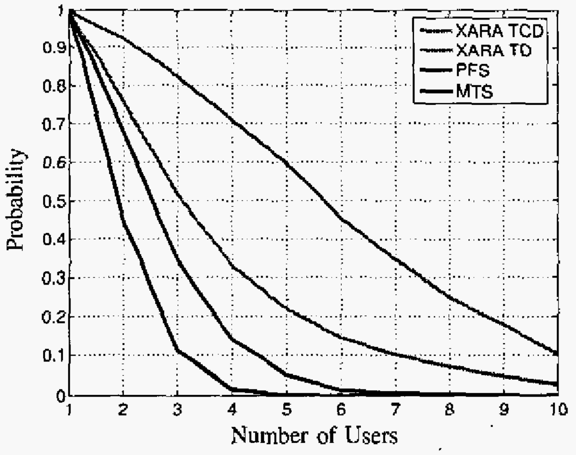

Fig. 3. Capacity Increase through XARA

V. CONCLUSION AND OUTLOOK

We presented a top-down cross-layer optimization, that allows to minimize the transmit power while serving a set of QoS requirements in multi-user systems. Within RRS, MTS and PFS algorithms have been considered and their effect on the QoS parameters throughput and delay have been included into the optimization. With the resulting technique the QoS management in multi-user systems is enabled, allowing for significant enhancements in transmit power as well as in servable system loads.

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