Adaptive QoS for Wireless Multimedia Networks Using Power Control and Smart Antennas

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***Abstract*—This paper addresses the problem of adaptive quality-of-service (QoS) for mobile multimedia services under a power controlled wireless network using smart antennas. Given the nature of multimedia, we chose the signal-to-interference and noise ratio (SINR) of each user's channel as the QoS index. We direct our attention toward two problems. The first is to increase the SINR levels for multimedia users as much as the system can provide for, under the channel fading and interference conditions. Different users have distinct desired SINR levels according to their requested service types; our algorithm uses an iterative method to drive the SINR levels as close as possible to those desired levels. The SINR levels are improved without deteriorating quality for other types of users. Simulations presented here show a significant increase in the average SINR levels for multimedia users. The second problem considered in this paper, is how to speedily initiate new users into the network by using lower complexity algorithms that yield reliable results. As shown in the simulations, our fast activation scheme can substantially reduce the time for activating new users into the system.**

***Index Terms*—Antenna arrays, interference suppression, mobile communication, multimedia communication, power control.**

I. INTRODUCTION

WIRELESS network technology has advanced to the point that providing multimedia services, e.g., video, voice, email, etc., to mobile telephony users is no longer a distant idea. Consider a wireless network with integrated multimedia services. Such a network requires that different users should be provided different qualities-of-service (QoS) to accommodate their distinct service types. There has been considerable attention devoted to this subject, where the term QoS has been used as an epithet for a variety of quality measures, such as packet dropping rate [1], [2], bit-error rate [3], resolution or quantization scale [4], packet delay [1], [5], and [6], bandwidth [3], [6], and [7], or channel quality or signal-to-interference and noise ratio (SINR) [8]. In this paper, the performance index will be the SINR levels [9], [10].

Using automatic power control and smart antennas, we propose to allocate and control the levels of SINR according to the individual need of each user and the quality of channels that the mobile system can allow, given the interference present at any given time. Each service type is assigned a target SINR level and our scheme endeavors to choose the transmission power assignments and receiver antenna weights that take the receiver SINR levels as close as possible to those target levels.

We address two problems: First, how to accommodate the SINR requirements for each user given his/her desired multimedia service type, and second, how to swiftly adopt and adapt users to the system. The latter point arises when the system is initiating service for a new user, whether the new user is initiating a call or if it is handing off from another base station. During this process, the system must calculate the power vector for all cochannel mobile users, and the antenna weights for all the associated base stations. These values can be obtained through iterative algorithms that require certain constraints for convergence, but these constraints may be lengthy to verify. In a practical situation, an extensive delay before activating the new users is not allowable. We present a technique that reduces the activation latency time for new multimedia service users. For this, we propose a fast and coarse method of finding the mobile powers and antenna weights. The technique we present to address the former problem, that is to draw the SINR levels as close to the users' target levels as possible, employs an iterative incremental procedure that increases the SINR levels for specific users and finds the optimal power vector for the new SINR set. This fine-tuning is done while the new users have already been activated, so there is no unsuitable delay for any user.

The subject of joint automatic power control and smart antennas has been addressed in [11], where a recursive least squares (RLS) algorithm is used to track a CDMA channel in the presence of cochannel interference, and an analysis is made of the gain provided by the smart antenna configuration. This work, does not address the individual channel qualities, nor does it propose to control them. In [12], the TDMA mobile radio standard IS-136 is the platform used to study the coverage area increase provided by joint-power control and smart antennas. However, the individual SINR levels granted to each user is not addressed. The quality level for individual users was addressed in [14], but the perspective is for providing several parallel lower-rate data streams. In [14], for high data rate users, the data sequences are first converted to several parallel basic-rate data streams, thus, more resources are allocated to these users. Resource assignment for mobile cellulars has been discussed in [15] from the perspective of channel assignment, or more extensively in [16], with a broader set of resources. But in both cases, they attempt to provide users with the QoS that is available, without changing mobile powers or antenna gains to create a better QoS for the users who need it.

The other new issue that this paper addresses, is that the existing trial and error techniques can be computationally long [12], [17], and [18]; and they may extend the time that new

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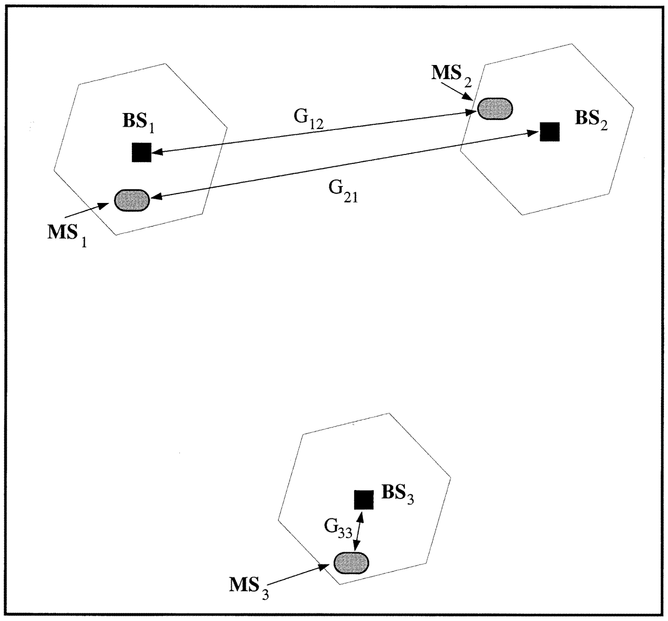

Fig. 1. The pathgains between mobiles and base stations are depicted here.

users must wait while powers and antenna weights are calculated. Our method exploits matrix theory tools that allow us to quickly find a solution for the new values to be calculated. This, in turn, translates to a faster service for new users.

The system model is described in Section II. The proposed technique for quick activation is described in Section III. The method for SINR fine-tuning for multimedia service users is explained in Section IV. The criteria for choosing the best SINR levels to adjust is described in Section V. The complete algorithm is put together for the reader in Section VI. Finally Sections VII and VIII have simulation results and conclusions, respectively.

II. General Model and Algorithm

Consider a wireless FDMA/TDMA network with M cochannel users employing automatic power control and using smart antennas. Minimum cochannel distances and formulas for the pathloss can be obtained from [19]. The variables that will be used in this paper are the following: BS_i represents the base station i, MS_j is the mobile station j, P_j is the transmitting power of the mobile station MS_j, $\mathbf{P}$ is the $M \times 1$ power vector for all cochannel mobile stations, and G_{ij} stands for the pathgain between MS_j and BS_i. As illustrated in Fig. 1, normally, $G_{ij} \neq G_{ji}$. The variable $\hat{\gamma}_i$ denotes the desirable SINR level for the BS_i receiver, given that the service type used by the MS_j user is known. The antenna weight $D \times 1$ vector, $\mathbf{w}_i$, contains the weights applied to the inputs to the antenna elements of BS_i. The vector $\mathbf{a}_{ij}$ is the $D \times 1$ array response of the BS_i array to the MS_j source. Finally, $\mathbf{N}_i$ is the $D \times 1$ vector of thermal noise at the antenna elements at the BS_i receiver.

The goal is to assign the effective SINR level, γ_i, according to each user's needs and test whether these SINR assignments can lead to optimum power allocations and antenna weights. The performance measure that has been used for controlling the smart antennas is the minimum noise variance criterion [12], [18], and [20]. Each antenna element of the antenna array of BS_i receives the signal from MS_i along with interfering signals arriving from different incident angles, as well as thermal noise.

Assuming a single signal from each mobile transmitter, the vector signal received at base station i is

$$\mathbf{x}_i(t) = \sqrt{P_i G_{ii}} s_i(t-\tau_i)\mathbf{a}_{ii} + \sum_{j\neq i} \sqrt{P_j G_{ij}} s_j(t-\tau_j)\mathbf{a}_{ij} + \mathbf{N}_i(t) \quad (1)$$

where $\mathbf{a}_{ij}$ is the array response vector from BS_i toward MS_j, and $s_j(t)$ is the signal from MS_j, τ_j is the propagation delay of signal $s_j(t)$, and

$$s_j(t) = \sum_n b_j(n) g(t-nT) \quad (2)$$

where $b_j(n)$ is the nth bit in the j the user's information stream, and $g(\cdot)$ is a pulse function. It has been shown that the output of a matched filter sampled at the symbol intervals, nT, is a sufficient statistic for the estimation of the transmitted signal [18]. By choosing the matched filter to be $g^*(-t)$, and sample the output at $t = nT$, the sampled output would be

$$\mathbf{x}_i(n) = \sqrt{P_i G_{ii}} b_i(n)\mathbf{a}_{ii} + \sum_{j\neq i} \sqrt{P_j G_{ij}} c_j(n)\mathbf{a}_{ij} + \mathbf{N}_i(n) \quad (3)$$

where $c_j(n)$ results from applying the matched filter to interfering signals. To simplify notation, leave n to be implicit in (3).

Fig. 2 shows how the antenna weights work on an incident beam

$$\mathbf{w}_i^H \mathbf{x}_i = \sqrt{P_i G_{ii}} b_i \mathbf{w}_i^H \mathbf{a}_{ii} + \sum_{j\neq i} \sqrt{P_j G_{ij}} c_j \mathbf{w}_i^H \mathbf{a}_{ij} + \mathbf{w}_i^H \mathbf{N}_i \quad (4)$$

where $\mathbf{w}^H$ is the Hermitian conjugate of the antenna array vector $\mathbf{w}$. The leftmost value of the right side of (1) is the desired signal and the rest are cochannel interference and noise. The goal of the minimum noise variance criterion is

$$\min_{\{\mathbf{w}_i\}_{i=1,\ldots,M}} \quad \mathbf{w}_i^H \cdot \Phi_i \cdot \mathbf{w}_i$$
$$\text{subject to } \mathbf{w}_i^H \cdot \mathbf{a}_{ii} = 1, \qquad i = 1, \ldots M \quad (5)$$

where $\Phi_i = E\{\mathbf{x}_i(t)\mathbf{x}_i^H(t)\}$, then the optimum weight vector that solves the problem described in (5) can be found to be, [20]

$$\hat{\mathbf{w}}_i = \frac{\Phi_i^{-1}\mathbf{a}_{ii}}{\mathbf{a}_{ii}^H \Phi_i^{-1} \mathbf{a}_{ii}}. \quad (6)$$

The optimal weight vectors are used to calculate the overall pathgain between bases and mobiles in power control. The purpose of power control is to select the transmitting power of each mobile station so as to have $\gamma_i \geq \hat{\gamma}_i$ for $i = 1, \ldots, M$, while minimizing the overall power used by all mobile stations. Here, γ_i is the effective SINR for user i, then

$$\gamma_i = \frac{G_{ii} P_i}{\sum_{j\neq i} G_{ij} |\mathbf{w}_i^H \mathbf{a}_{ij}|^2 P_j + n_i} \quad (7)$$

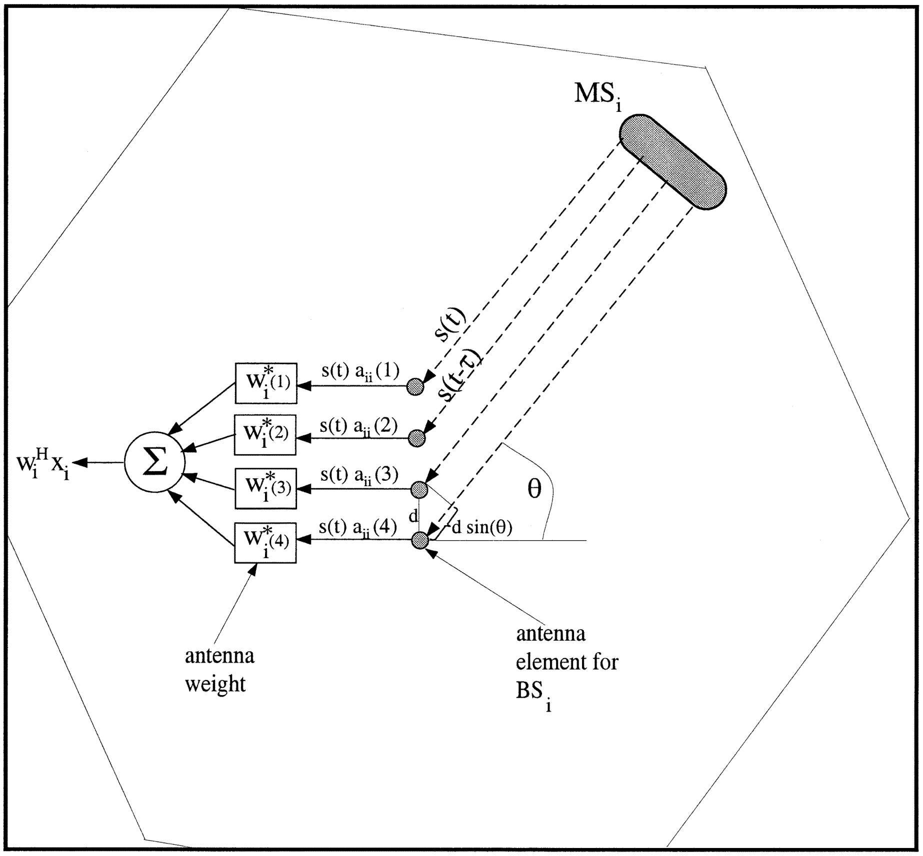

Fig. 2. Mobile station i is far enough that it is assumed that the signal is incident on all antenna elements at the same angle θ.

where $n_i = \mathbf{w}_i^H \tilde{N}_i \mathbf{w}_i$, and $\tilde{N}_i$ is the noise power at the ith receiver. Given that pathgains and powers are nonnegative, the vector version of the constraint is

$$\mathbf{P} - \Gamma F \mathbf{P} \geq \begin{pmatrix} \gamma_1 \dfrac{n_1}{G_{11}} & \gamma_2 \dfrac{n_2}{G_{22}} & \cdots & \gamma_M \dfrac{n_M}{G_{MM}} \end{pmatrix}^T \tag{8}$$

where $\Gamma = \mathrm{diag}(\gamma_1, \ldots, \gamma_M)$, as shown in the equation at the bottom of the page.

We will label the right-side vector in (8) as $\mathbf{u}$. The problem statement for the power control problem is now given by

$$\begin{aligned} &\text{minimize} \quad \sum_{i=1}^{M} P_i \\ &\text{subject to} \quad (I - \Gamma F)\mathbf{P} \geq \mathbf{u}. \end{aligned} \tag{9}$$

The spectral radius of a matrix is its eigenvalue with the largest norm. If the antenna weights remain constant, it has been shown [21], [22] that, if the spectral radius of ΓF is inside the unit circle

$$|\rho(\Gamma F)| < 1 \tag{10}$$

then the optimum power vector for this constrained problem is

$$\hat{\mathbf{P}} = (I - \Gamma F)^{-1}\mathbf{u}. \tag{11}$$

An optimal solution can be obtained if there exists any *feasible* set of weight vectors, $\{\mathbf{w}_i\}_{i=1,\ldots,M}$ in the complex plane such that $\rho(\Gamma F) < 1$ [18]. However, finding a feasible set of vectors involves an extensive search. The goal of this paper is to determine that for the most favorable Γ possible. This problem can be considered as a problem of perturbing the matrix Γ, with

$$F = \begin{pmatrix} 0 & \dfrac{G_{12}|\mathbf{w}_1^H \mathbf{a}_{12}|^2}{G_{11}} & \cdots & \dfrac{G_{1M}|\mathbf{w}_1^H \mathbf{a}_{1M}|^2}{G_{11}} \\ \dfrac{G_{21}|\mathbf{w}_2^H \mathbf{a}_{21}|^2}{G_{22}} & 0 & \cdots & \dfrac{G_{2M}|\mathbf{w}_2^H \mathbf{a}_{2M}|^2}{G_{22}} \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{G_{M1}|\mathbf{w}_M^H \mathbf{a}_{M1}|^2}{G_{MM}} & \dfrac{G_{M2}|\mathbf{w}_M^H \mathbf{a}_{M2}|^2}{G_{MM}} & \cdots & 0 \end{pmatrix}$$

the intention of keeping $|\rho(\Gamma F)| < 1$. Consider these perturbations to be additive and also consider the perturbation on each γ_i as a separate perturbation. We can rewrite the question as: Is there a collection, $\{t_i\}_{i=1,\ldots,M}$, with $t_i \in [-1, 1]$, $i = 1, \ldots, M$, such that

$$\rho\left(\Gamma F + \sum_{i=1}^{M} t_i \Delta\gamma_i \Gamma_i F\right) < 1? \tag{12}$$

In this equation, Γ_i is a matrix whose ith diagonal element is one and all other elements are zero, and $\Delta\gamma_i$ is the maximum perturbation considered for each SINR level. In [23], it is shown that this problem is NP-complete. Therefore, an optimal solution cannot, in general, be obtained with polynomial time algorithms. Obtaining the optimal Γ, while retaining the strict inequality in (12), would be NP-hard. Here we propose an iterative algorithm, which perturbs the SINR levels and tests for convergence, while using norms of lower complexity whenever possible.

III. Method for Quick Activation

The need for speedy decisions in a mobile environment is clear. When a new user initiates a call, the system must choose the best base station for service, the best frequency band, a new power vector, antenna gains, and the decision process for these as well as many other factors should be transparent to users. This section presents a novel scheme to quickly establish converging SINR levels which lead to the optimal power vector and the antenna weights.

It has been seen that the test for convergence for the joint power control/beamforming solution requires an extensive search over all the complex plane for M D-dimensional vectors that both comply with $\mathbf{w}_i^H \mathbf{a}_{ii} = 1$ and also have $\rho(\Gamma F) < 1$. It is desirable to perform this test for the best possible Γ.

The system may be forced to make many attempts before finding the best Γ that is feasible. Also, it is not clear which γ_i should be lowered to yield faster convergence. The following presents a quick test for convergence that yields fast knowledge of the feasibility of a certain Γ.

The idea is to use norm one for the convergence test rather than the spectral radius of the matrix ΓF. Norm one will also yield an acceptable answer: if $(\Gamma F) \in \Re^{n\times n}$ and $\|(\Gamma F)\| < 1$, then $(I - \Gamma F)$ is nonsingular with $(I - \Gamma F)^{-1} = \sum_{k=0}^{\infty} (\Gamma F)^k$, [24]. The nonnegative elements of (ΓF) guarantee that the inverse has nonnegative elements, which results in a nonnegative power vector in (11).

Caution must be used since, even though it is clear that the spectral norm can be replaced with this simpler norm one, the spectral radius should be used in the fine-tuning stage. This is because, though difficult to handle, the spectral radius is a more precise indicator of the convergence of the power control algorithms, since $\rho(A) \le \|A\|$ for all consistent norms [25].

The above norm inequality means that there may be matrices such that $\rho(\Gamma F) < 1$, yet $\|\Gamma F\|_1 \ge 1$. In these cases, the faster norm will push the algorithm to reduce the SINR for the new users, even though it is not necessary for convergence. This is the price for using a lower-complexity norm.

First, we decompose the matrix F into three matrices, thus, separating the weights from the other variables. Denote the collections of weights, pathgains, antenna gains, and SINR levels by

$$\begin{aligned} \mathcal{W} &= \{\mathbf{w}_1, \mathbf{w}_2, \ldots, \mathbf{w}_M\} \\ \mathcal{G} &= \{G_{ij}\}_{i,\, j\in\{1,\ldots,M\}^2} \\ \mathcal{A} &= \{\mathbf{a}_{ij}\}_{i,\, j\in\{1,\ldots,M\}^2} \end{aligned}$$

and

$$\Upsilon = \{\gamma_1, \gamma_2, \ldots, \gamma_M\}.$$

Then

$$\Gamma F = L(\mathcal{W}) \cdot M(\Upsilon, \mathcal{G}, \mathcal{A}) \cdot R(\mathcal{W}) \tag{13}$$

where the $M \times DM$ matrix L is

$$L(\mathcal{W}) = \begin{pmatrix} \mathbf{w}_1^H & 0 & \cdots & 0 \\ 0 & \mathbf{w}_2^H & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{w}_M^H \end{pmatrix} \tag{14}$$

the $DM^2 \times M$ matrix R is

$$R^T(\mathcal{W}) = \begin{pmatrix} \psi_1^* & \psi_2^* & \cdots & \psi_M^* \end{pmatrix}^T \tag{15}$$

where each $DM \times M$ submatrix ψ_i is:

$$\psi_i = \begin{pmatrix} \mathbf{w}_i & 0 & \cdots & 0 \\ 0 & \mathbf{w}_i & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{w}_i \end{pmatrix} \tag{16}$$

and $*$ indicates complex conjugate. And finally, the $DM \times DM^2$ central matrix is

$$M(\Upsilon, \mathcal{G}, \mathcal{A}) = \begin{pmatrix} \mathbf{f}_1 & 0 & \cdots & 0 \\ 0 & \mathbf{f}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{f}_M \end{pmatrix} \tag{17}$$

where each $1 \times M$ vector $\mathbf{f}_i$ is

$$\mathbf{f}_i = \left(\frac{\gamma_i G_{i1} \mathbf{a}_{i1} \mathbf{a}_{i1}^T}{G_{ii}} \quad \cdots \quad \frac{\gamma_i G_{ii-1} \mathbf{a}_{ii-1} \mathbf{a}_{ii-1}^T}{G_{ii}} \quad 0 \quad \frac{\gamma_i G_{ii+1} \mathbf{a}_{ii+1} \mathbf{a}_{ii+1}^T}{G_{ii}} \quad \cdots \quad \frac{\gamma_i G_{iM} \mathbf{a}_{iM} \mathbf{a}_{iM}^T}{G_{ii}} \right). \tag{18}$$

The prohibitively large dimensions of these matrices should not be a discouragement, since these matrices will not affect any computation, and most matrix elements are zero.

Now, these matrices are used to answer the convergence question: With this Γ, is $\|\Gamma F\|_1 < 1$? If

$$\|L\|_1 \cdot \|R\|_1 < \frac{1}{\|M\|_1} \tag{19}$$

then, since norm one is consistent

$$\|\Gamma F\|_1 \le \|L\|_1 \cdot \|M\|_1 \cdot \|R\|_1 < 1. \tag{20}$$

Note that

$$\|L\|_1 = \max_{1\le j\le M} \|\mathbf{w}_j\|_\infty \tag{21}$$

$$\|R\|_1 = \sum_{j=1}^{M} \|\mathbf{w}_j^*\|_1 \tag{22}$$

and

$$\|M\|_1 = \max_{i,\,j,\,k}\left\{\frac{\gamma_i G_{ij}}{G_{ii}}\,\alpha_{ij}(k);\, 1\le i,\, j\le M,\, 1\le k\le D\right\} \tag{23}$$

where $\alpha_{ij}(k)$ is the kth column of the $D\times D$ matrix $\mathbf{a}_{ij}\mathbf{a}_{ij}^T$. Therefore, it suffices to find a set of vectors, $\{\mathbf{w}_i\}_{i\in I}$ such that

$$\mathbf{w}_i^H\mathbf{a}_{ii} = 1, \qquad i = 1,\ldots,M \tag{24}$$

and

$$\max_{j=1,\ldots,M} \|\mathbf{w}_j\|_\infty \cdot \sum_{i=1}^{M} \|\mathbf{w}_i\|_1 < \frac{1}{\|M\|_1}. \tag{25}$$

Note that the system does not control the variables in the right-hand side of this inequality. Except for the γ_i, the right-hand side must be estimated from the system. The pathgains may be estimated with training signals, or a joint estimation of pathgains and antenna array response vectors may be obtained by procedures outlined in [13]. If there is a set of vectors that complies with these constraints, then $(I-\Gamma F)$ in (11) has an inverse and $\hat{P}$ is the optimal power vector for these SINR. Therefore, the test is resolved when a set of vectors that minimize the left-hand side of inequality (25) is found.

Theorem 1: The collection of vectors, $\{\tilde{\mathbf{w}}_i\}_{i\in I}$, that minimizes the left-hand expression of (25), under the constraint of (24) has vectors with the following elements

$$\tilde{w}_i[k] = \begin{cases} \dfrac{1}{a_{ii}^*[k]} & k = \arg\max_{j=1,\ldots,D} |a_{ii}[j]| \\ 0, & \text{otherwise.}\end{cases} \tag{26}$$

Proof: Clearly, $\tilde{\mathbf{w}}_i^H\mathbf{a}_{ii} = 1$, for $i = 1,\ldots,M$. Now, suppose that there is some other set of vectors, $\{\mathbf{y}_i\}_{i\in I}$ such that $\mathbf{y}_i^H\mathbf{a}_{ii} = 1$ for $i = 1,\ldots,M$. By the definition of the array response vector in [20], we know that $\|\mathbf{a}_{kk}\|_\infty = 1$, for $k = 1,\ldots,M$, so

$$\min_{k=1,\ldots M} \|\mathbf{a}_{kk}\|_\infty \cdot \sum_{i=1}^{M} \|\mathbf{y}_i\|_1 = \sum_{i=1}^{M} \|\mathbf{y}_i\|_1 \cdot \|\mathbf{a}_{ii}\|_\infty. \tag{27}$$

Now, by the Holder inequality [22], (27) yields

$$\sum_{i=1}^{M} \|\mathbf{y}_i\|_1\|\mathbf{a}_{ii}\|_\infty \ge \sum_{i=1}^{M} |\mathbf{y}_i^H\mathbf{a}_{ii}| = M. \tag{28}$$

On the other hand

$$\frac{1}{\max\limits_{k=1,\ldots,M}\|\mathbf{y}_k\|_\infty}\cdot\sum_{i=1}^{M}\frac{1}{\|\mathbf{a}_{ii}\|_\infty} \le \sum_{i=1}^{M}\frac{1}{\|\mathbf{a}_{ii}\|_\infty}\cdot\frac{1}{\|\mathbf{y}_i\|_\infty} \le \sum_{i=1}^{M}\frac{1}{\|\mathbf{y}_i^H\mathbf{a}_{ii}\|_\infty} = M. \tag{29}$$

It follows from (27)–(29), that

$$\min_{k=1,\ldots,M} \|\mathbf{a}_{kk}\|_\infty \cdot \sum_{i=1}^{M} \|\mathbf{y}_i\|_1 \ge M \ge \frac{1}{\max\limits_{k=1,\ldots,M}\|\mathbf{y}_k\|_\infty}\cdot\sum_{i=1}^{M}\frac{1}{\|\mathbf{a}_{ii}\|_\infty}.$$

So

$$\begin{aligned}\max_{k=1,\ldots,M} \|\mathbf{y}_k\|_\infty \cdot \sum_{i=1}^{M} \|\mathbf{y}_i\|_1 &\ge \max_{k=1,\ldots,M}\left(\frac{1}{\|\mathbf{a}_{kk}\|_\infty}\right)\cdot\sum_{i=1}^{M}\frac{1}{\|\mathbf{a}_{ii}\|_\infty}\\ &= \max_{j=1,\ldots,M}\|\tilde{\mathbf{w}}_j\|_\infty\cdot\sum_{i=1}^{M}\|\tilde{\mathbf{w}}_i\|_1. \qquad \diamond\end{aligned}$$

Therefore, the power control problem (9) has an element by element positive solution, as in (11), if

$$\frac{1}{\min\limits_{k=1,\ldots,M}\|\mathbf{a}_{kk}\|_\infty}\sum_{i=1}^{M}\frac{1}{\|\mathbf{a}_{ii}\|_\infty} < \frac{1}{\|M\|_1}. \tag{30}$$

It is worth repeating that if inequality (30) does not hold, the question of whether or not there will be convergence to a power vector and antenna weights is not clear. Such reduced resolution is the tradeoff for the decreased complexity.

Inequality (30) results in a simple test for determining if the system with the new users will yield a positive-power vector..

IV. SINR Fine-Tuning for Adaptive QoS

In the previous section, we can find a feasible matrix, Γ, that guarantees convergence to the optimal power vector and antenna weights. With this, the new users can be activated and served in the network. Next, the goal is to improve as many γ_i as possible, while still being able to arrive at the optimal power vector and antenna weights. We seek to improve the SINR levels, γ_i, while controlling the behavior of the spectral radius of the matrix ΓF. When we increase an SINR level, we do not wish $|\rho(\Gamma F)|$ to exceed one. Conversely, when $|\rho(\Gamma F)|$ is above one, we wish to force it back down with the minimum-possible lowering of any SINR level. The tools used to make these choices are $\{\partial\rho(\Gamma F)/\partial\gamma_i\}_{i\in I}$ since they describe the rate of change of $\rho(\Gamma F)$ with respect to each γ_i. Here, $I\subseteq\{1,\ldots,M\}$ is the subset of users who are assigned high SINR levels, for their service types. First, assume that these derivatives exist, and they have been sorted from the smallest to the largest. Since the spectral radius of a matrix is a lower bound for its norm one, the Γ that complies with (30) will also comply with (10). The next step, after performing the quick activation for new users is to increase the SINR level for user

$$i_{\text{des}} = \arg\min_{i\in I}\frac{\partial\rho}{\partial\gamma_i}. \tag{31}$$

Once the i_{des} is selected, $\gamma_{i_{\text{des}}}$ is increased and inequality (10) is tested for convergence. The antenna beam former directs a

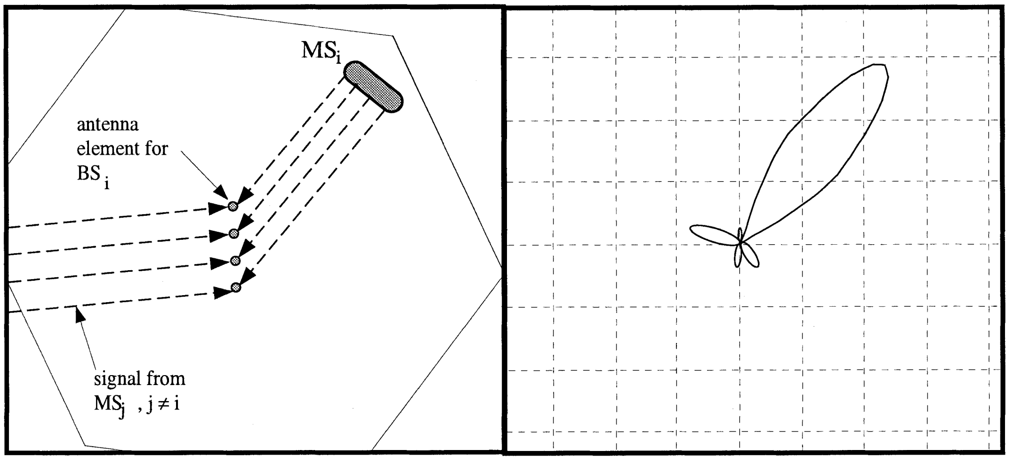

Fig. 3. A BS with an incoming desired signal and an undesired signal can be observed. We assume that in a short period of time, this antenna beam need not be significantly altered.

large gain toward the desired signal and a small gain toward the interferers. If the test period is short enough, we can assume that the positions of the mobiles do not change significantly during that time span (see Fig. 3), i.e., the antenna weights need not be recalculated. A new power vector that is more favorable to user $i_{\rm des}$, while not chastising the other users, can be obtained and implemented.

If the test fails, that is $|\rho(\Gamma' F)| \geq 1$, then some SINR level should be reduced to bring $|\rho(\Gamma' F)|$ down again. Rather than reducing $i_{\rm des}$, the SINR for a different user

$$i_{\rm red} = \arg \max_{i \in I'} \frac{\partial \rho}{\partial \gamma_i} \tag{32}$$

is reduced because we expect the reduced amount from user $i_{\rm red}$ should be less, or at most equal, to the amount that should be reduced from $i_{\rm des}$. The test for convergence is repeated. This procedure is repeated until the test is passed. Here, $I' \subset I$ is the subset of I, which contains the user indexes for users who have a current SINR assignment that is above their minimum allowable level. All users are required to have an SINR level above some predetermined amount. If the fine-tuning algorithm reduces all γ_i to the point where all have reached their minimum allowable level, and still $|\rho(\Gamma' F)| \geq 1$, then some call must be dropped. This is the same method as is used in current power control, where a call is dropped if $1 \| \rho(F)|$ is less than the lowest allowable SINR level [18].

The system can continue using this method of increasing the SINR levels as much as possible until new users request activation in the system. After some time, it is no longer possible to assume that the mobile units have not moved significantly, so the system must recalculate the weight vectors as well as the power vector. The algorithm will be summarized in Section V.

This suboptimal approach may not yield the global optimal solution because there are a number of local minima. The proposed method implements a steepest descent algorithm that may lead ultimately to a local minimum. Therefore, careful choices of the size of increments and reductions may lead to better results.

V. Criteria for SINR Adjustment

This section deals with the question of choosing which SINR to adjust to best fit the purpose described in the previous two sections. It is necessary to calculate the derivative of $\rho(\Gamma F)$ with respect to each γ_i. The question of the existence of the derivative of the spectral radius of such a matrix is addressed in [25], in conjunction with Frobenius' Theorem which says: *A nonnegative, irreducible matrix always has a positive characteristic value, r, that is a simple root of the characteristic equation. The moduli of all other characteristic values do not exceed that of r* [22]. An expression for the derivative is now derived.

Theorem 2: Let ρ be a simple eigenvalue of ΓF, with right and left eigenvectors, $\mathbf{x}$ and $\mathbf{y}$, respectively. Let $\tilde{F} = \Gamma F + E$. Then there exists a unique $\tilde{\rho}$, eigenvalue of $\tilde{F}$ such that

$$\tilde{\rho} = \rho + \frac{\mathbf{y}^H E \mathbf{x}}{\mathbf{y}^H \mathbf{x}} + \mathcal{O}\left(\|E\|^2\right). \tag{33}$$

Proof: [25, pp. 183–184]. ◇

In the application at hand

$$\begin{aligned} E &= \begin{pmatrix} 0 & & & & \\ & \ddots & & 0 & \\ & & \Delta\gamma_i & & \\ & 0 & & \ddots & \\ & & & & 0 \end{pmatrix} \cdot F \\ &= \Delta\gamma_i \underbrace{\begin{pmatrix} 0 & \cdots & 0 \\ 0 & \cdots & 0 \\ \dfrac{G_{i1}|\mathbf{w}_i^H \mathbf{a}_{i1}|^2}{G_{ii}} & \cdots & \dfrac{G_{iM}|\mathbf{w}_i^H \mathbf{a}_{iM}|^2}{G_{ii}} \\ 0 & \cdots & 0 \end{pmatrix}}_{\triangleq F_i}. \end{aligned} \tag{34}$$

From (33) and (34), we have

$$\frac{\partial \rho}{\partial \gamma_i} = \frac{\mathbf{y}^H F_i \mathbf{x}}{\mathbf{y}^H \mathbf{x}}. \tag{35}$$

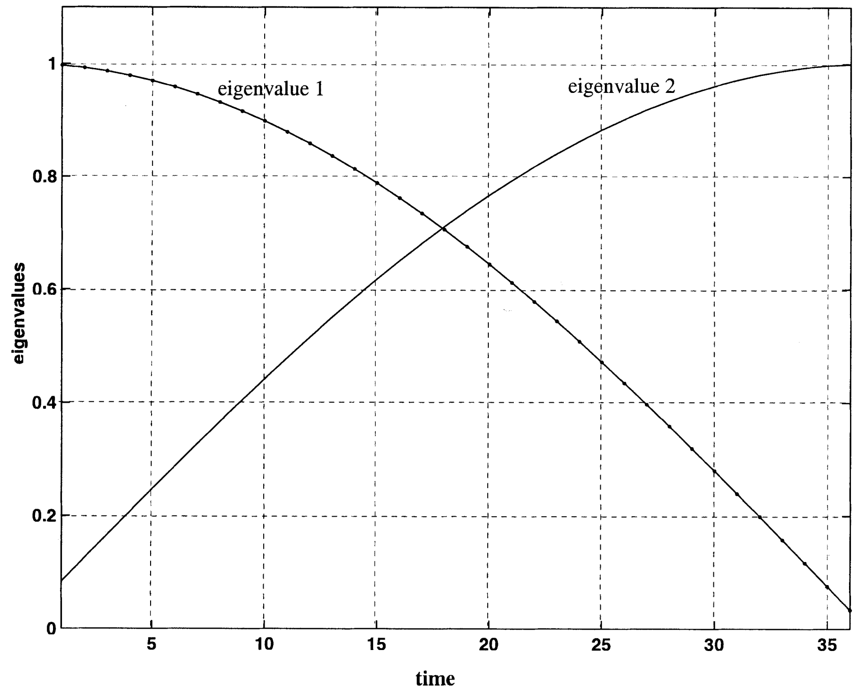

Fig. 4. As the norm of one eigenvalue grows and the norm of another shrinks, the intersection of the two values results in a point which is not smooth for ρ.

TABLE I
INTEGRATED MULTIMEDIA QoS ALGORITHM

Step	Action
1.	Check system for new cochannel users.
2.	Assign the desired γ to new users according to their service type (e.g. voice, image, video, etc).
3.	Calculate $\|\|M\|\|_1$ with initial Γ.
4.	Test if there exist $\{\mathbf{w}_i\}_{i\in I}$ such that $\|\|L\|\|_1\|\|R\|\|_1 < \frac{1}{\|\|M\|\|_1}$. See (30).
4.a.	If (30) holds, then this Γ works; proceed to step 5.
4.b.	If (30) does not hold, reduce the γ_i of Γ whose index corresponds to the highest $\frac{\partial\rho(\Gamma F)}{\partial\gamma_i}$, as described in (32). Return to Step 4.
5.	Obtain $\{\mathbf{w}_i\}_{i\in I}$ and $\mathbf{P}$ through direct matrix inversion or an iterative process.
6.	Assign antennas weights to bases and transmit power settings to mobile units.
7.	Increase the γ_i of Γ whose index corresponds to the lowest $\frac{\partial\rho(\Gamma F)}{\partial\gamma_i}$, as described in (31). Call this new set of SINR levels Γ_{new}.
8.	Check to see if new mobiles have been added or if the clock has timed out. If so, go to Step 1, otherwise continue to Step 9.
9.	Check if $\rho(\Gamma_{new}F) < 1$.
9.a.	If the inequality holds, Γ_{new} allows for convergence for the power vector calculation. Go to Step 10.
9.b.	If the inequality does not hold, reduce the γ_i of Γ whose index corresponds to the highest $\frac{\partial\rho(\Gamma F)}{\partial\gamma_i}$, as described in (32). Got to Step 7.
10.	Check if $\|\|\Gamma_{new} - \Gamma\|\| > 0$.
10.a.	If Γ_{new} is better than Γ, go to Step 11.
10.b.	If not, estimate new path gains and go to Step 7.
11.	Obtain power vector, $\mathbf{P}$, through matrix inversion or an iterative method. Go to Step 6.

Note that the denominator is constant for all $i = 1, \ldots, M$. For a set of numbers, $X = \{x_0, x_1, \ldots, x_N\}$, let$\mathcal{S}\{x_0, x_1, \ldots, x_N\}$ denote the ordered N-tuple of indexes of the elements of X, sorted by the magnitude of the elements. Then, the derivatives of (35) can be sorted

$$\mathcal{S}\left\{\left\{\frac{\mathbf{y}^H F_i \mathbf{x}}{\mathbf{y}^H \mathbf{x}}\right\}_i\right\}_{i\in I} = (i_0, i_1, \ldots, i_{\langle I\rangle}). \tag{36}$$

Several SINR may be candidates for reduction at once, but the decision of *which* ones and *by how much* should be influenced by the sorted indexes. The criteria for choosing the γ_i may still have some subjective contribution. For example, even if a certain user, j, has the higher derivative, that user may not be chosen as the candidate if he has been functioning with a high quality, or pays a higher tariff. It would perhaps make more sense to take the subset of new users and only work with their SINR. Another consideration is that certain users may have been considered repeatedly for reduction during the iterations. It may be desirable to tag users so that they do not suffer repeated quality deprivation. These considerations have been included in the simulations in Section VI.

It should be noted that the derivative is a measure of infinitesimal change, therefore, small perturbations of the γ_i should be chosen, so that these results may have some value. Another reason to keep the perturbations small is that a large perturbation could cause several eigenvalues to change in value. Even though each eigenvalue is continuous with respect to the matrix values, the spectral radius is always the eigenvalue with the largest magnitude. If the eigenvalue that is currently the spectral radius is reduced, and another eigenvalue increases in norm, then the spectral radius may change from the first eigenvalue to the second. This would result in a problem where the spectral radius is not smooth with respect to changes in the matrix values. This is illustrated in Fig. 4, where each eigenvalue changes smoothly, but the spectral radius is not smooth at the point of intersection. At that point, the derivative does not exist.

VI. The Adaptive QoS Algorithm

In this section, a working algorithm is formulated with the ideas presented in the previous sections. The algorithm is listed in Table I. Fig. 5 is a flowchart of the algorithm.

If there is no convergence even after repeated SINR reduction, and an optimal power vector cannot be obtained, then the system should perform a handoff to another frequency band for some user. This can be a change of frequency bands within the same base station, to another base station whose service area overlaps with the current base station's service area. As a last resort, the system may have to drop a call.

VII. Simulation Results

The platform for the simulations is a wireless network with M cochannel users using FDMA/TDMA, and a (2, 1) reuse pattern.[1] Each base station has four antenna elements. For the purposes of this simulation, only two user service types are considered, e.g., voice quality and video quality. The algorithm can be readily extended to several quality types. It is assumed that voice users require γ_v, and they would get that quality without adjustment. The SINR level γ_m, is considered to be the default level for video service. The latter is considerably higher than γ_v (of the order of 16 dB higher). In all simulations, no user was permitted to have an SINR level below γ_v.

The algorithm that were used for the simulations in this paper has one additional constraint that was not listed in the algorithm of Section VI. This was added to the Fast Activation scheme. If SINR levels must be decreased during Fast Activation, the only SINR levels considered for reduction are the new users'. This was implemented so that existing users would not suffer detrimental effects every time new users were activated.

[1]This reuse pattern means that for any given base station, the closest base station that uses the same frequencies is two bases away along the horizontal axis, and one base away along the 60° axis. This is also referred to as the seven-cell reuse pattern.

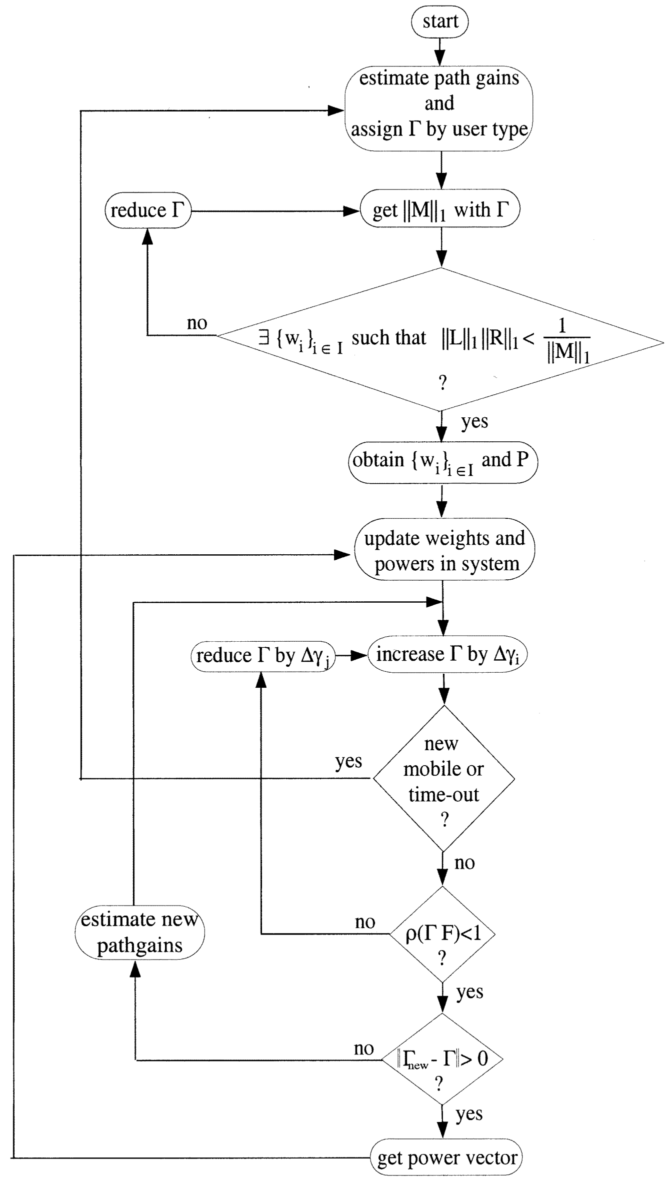

Fig. 5. Flowchart for the algorithm

The simulations presented run along a time axis. M is the maximum number of cochannel calls that may be working at any given time. For both examples in Figs. 6 and 7, $M = 40$. It is assumed that about 80% of those forty links would be on at any given time, and of the ones that are on, p proportion of them desire a video quality channel. Call lengths are exponentially distributed with an average length of six minutes. At any given time, half of the users are static, and the other half are moving at a constant speed in a random direction. Users which leave the service area of a base station must hand off to another base station with another carrier and another time-slot, so for the purposes of our algorithm, they are treated as a terminated call. The time-out for exiting Steps 8–10 of the algorithm in Table I was set to be 16 seconds times the number of active users. More time would allow for further fine-tuning.

In Fig. 6, the SINR level γ_v is indicated with a dotted line at 18 dB, and γ_m is also indicated with a dotted line at 32 dB. In the simulation, the effective SINR levels were averaged over all

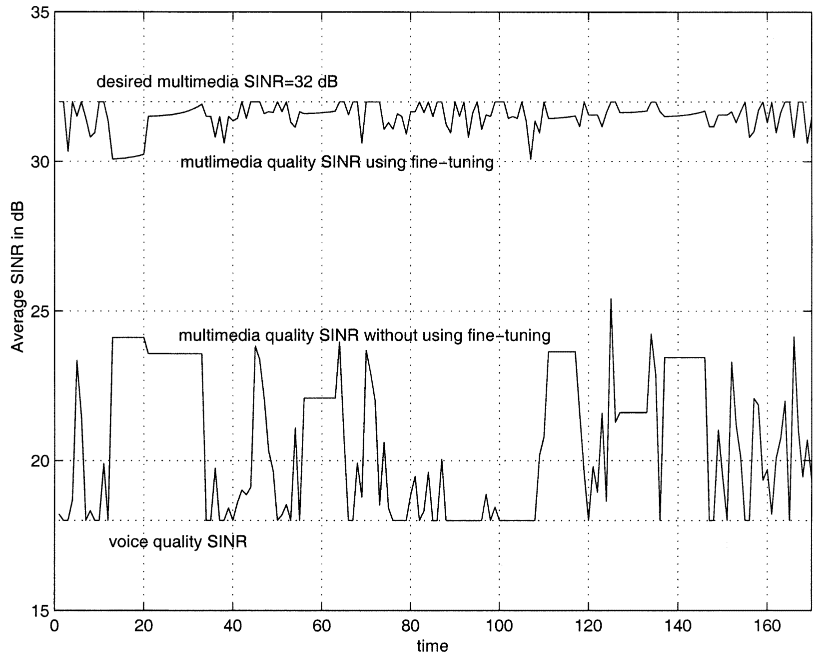

Fig. 6. SINR averaged over all multimedia users at each time instant. Two scenarios are presented here, one where the fine-tuning procedure is not used, and one where the fine-tuning procedure is used. Here, $M = 40, p = 0.3$; $\gamma_v = 18$ dB; $\gamma_m = 32$ dB.

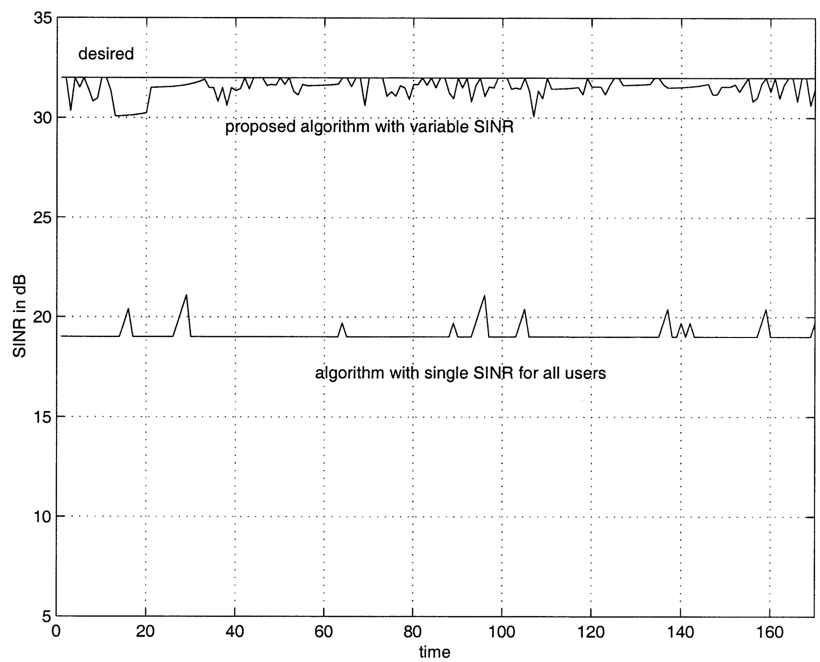

Fig. 7. Here we compare the SINR for multimedia users at each time instant for the case where all users must have the same SINR, as opposed to allowing different users to have distinct SINR levels. $M = 40, p = 0.3$; $\gamma_v = 18$ dB; $\gamma_m = 32$ dB.

video service users at each time instant and plotted in Fig. 6. The curve that is closer to γ_v is the average SINR level for video service users if the fast activation scheme, presented in Section III, is implemented, but the SINR fine-tuning scheme, presented in Section IV, is not implemented. The curve that is near γ_m is the effective average SINR level for video service users if both the fast activation scheme and the fine-tuning scheme are implemented. As can be seen, the SINR fine-tuning process has a large impact on the average SINR levels for the video service users. The time averaged difference between the SINR levels for multimedia users and their desired level for the method without SINR fine-tuning was 11.4 dB. The time averaged difference for those users using the fine-tuning was 0.5 dB. This means that the fine-tuning scheme we present yielded roughly an improvement of 10.9 dB. The variance for the curve that reflects the fine-tuning technique is 0.2307 and the variance for the curve without the fine-tuning is 5.8345.

For Fig. 7, the desired SINR level for video service users is marked at 32 dB. The experiment considered here compares a service where video users have distinct SINR levels that are ad-

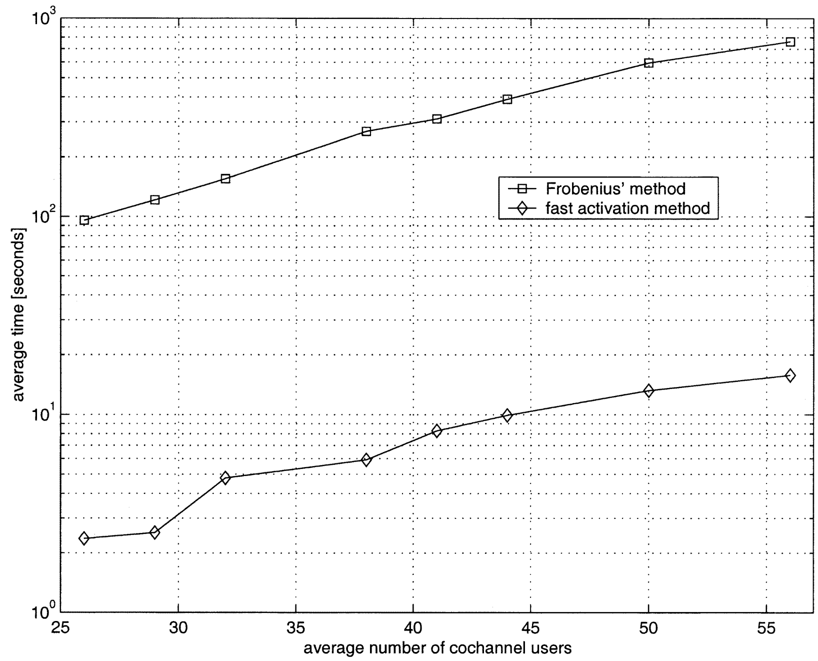

Fig. 8. Comparison of the processing time for the fast activation method proposed in this paper to a trial and error method.

justed independently to another service that provides the same SINR level for all video users and they are all adjusted simultaneously, and by the same amount. At each moment in time, the SINR levels for all video service users is averaged and plotted. The curve that is near γ_m is the average SINR for video service users in a system using the proposed algorithm. The curve that is below that is the average SINR level for video service users for a system that keeps all SINR levels the same for video service users. In the latter system, a single SINR level is applied to all users, without the benefit of the criteria for γ_i selection, as described in Section V. The tests for convergence performed for fast activation and fine-tuning are carried out in the same way as we have described, but the adjustments are done to all video SINR levels equally. As can be observed in Fig. 7, the freedom to permit different SINR levels to different users provides a significant improvement to the average SINR level for video service users. The average SINR for the system that uses our algorithm is 31.5 dB with a variance of 0.23. The average SINR for the system imposing the same SINR level for video users is 19.2 dB with a variance of 0.17.

Fig. 8 compares the time that our scheme takes to calculate the mobile powers and antenna weights when new users are being added to a system that doesn't use preconvergence testing, such as [18]. In the latter scheme, the desired γ_m is assigned to the new users. The system then engages in an iterative algorithm to get the powers and antenna weights. If the algorithm did not converge in $4 \cdot M$ iterations, it would reduce the SINR for a randomly chosen video user and try again. This experiment was repeated for different values of M. Since at any given time roughly 80% of M cochannel users are on, the x axis of Fig. 8 is the average number of users that are operating for each M. For each M, the system was simulated to work for almost three hours, and the time to calculate the power vector and antenna weights for new users that requested service was recorded and the average was taken at the end of each experiment. As can be seen in Fig. 8, the fast activation method is considerably faster than the method that does not use pre-convergence testing. Both curves increase as M increases, as expected, but the fast activation method is consistently over 15 times faster than the method that does not use preconvergence testing.

VIII. Conclusion

A significant increase in the receiver SINR for certain users can be gained by estimating the spectral properties of the system matrix and using those properties to adjust the power for the mobile units. This paper presented an algorithm that permits different users to be assigned different SINR levels depending on the interference levels local to each user. The algorithm includes a SINR fine-tuning scheme that optimally chooses video service users who should be targeted for an increase in their SINR levels. For the system in our simulations, where the desired SINR for voice users was 18 dB, and that for video users was 32 dB, the results show over 10 dB of improvement of the SINR by using the proposed SINR fine-tuning scheme.

The proposed algorithm also includes a fast activation scheme that uses properties of matrix theory to reduce the computational complexity involved in some parts of call initiation. Simulation results show that the fast activation scheme managed to significantly reduce the time for calculating the power vector and antenna weights when there are new users, by using a coarser and faster method for finding feasible SINR. The simulations, performed for several system sizes, have consistently shown an improvement over a factor of 15 in the average time required to find a feasible solution.

One advantage to our iterative method for improving the SINR for video service users is that the new users are activated faster than with existing methods, and the fine-tuning scheme guarantees no detriment to voice quality users, while it seeks to drive the SINR closer to the desired levels.

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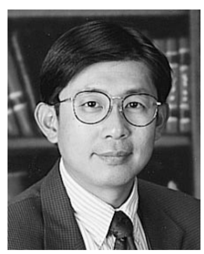

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