Steffensen iterations for power updates in CDMA wireless networks*

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Abstract— In this paper we present a new algorithm for mobile power updates in wireless CDMA systems. The algorithm in fact represents accelerated Jacobi iterations for mobile power updates of the algorithm popularly known as the DPC (distributed power control) algorithm. The new algorithm, with more rapid convergence, is obtained using Steffensen fixed-point iterations initialized by two Jacobi iterations. With minor extensions the Steffensen iteration algorithms presented can be used to accelerate the constrained version of the DPC algorithm. We present simulation results using realistic data to illustrate the improved convergence of the new algorithm as compared with the DPC and the second-order power control (SOPC).

I. Introduction

In recent years, there has been increasing interest in applying code-division-multiple-access (CDMA) techniques to cellular wireless networks. Unlike narrowband systems, users in a CDMA system share the same frequencies all the time by using a specific spread spectrum pseudonoise code for each user. The system performance mainly depends on so-called multiple access interference, which is caused by the cross-correlations between the desired signal and other signals. In a cellular wireless network, certain quality-of-service (QoS) should be maintained for all active users in the network. A quantity that measures the user's provided QoS is the signal-to-interference ratio (SIR). The importance of proper power control in wireless networks is discussed in papers by Rosberg and Zander[26]; Bambos[3]; Hanly and Tse[16].

In the uplink (mobile-to-base) power control problem with active users in a CDMA wireless system, the SIR ratio is defined as follows

$$\gamma_i = \frac{g_{ii} p_i}{\sum_{j \neq i} g_{ij} p_j + \sigma_i^2} \tag{1}$$

where p_i is the transmission power for user i, g_{ij} denotes an effective link gain from the jth mobile station to the base station that specifies the jth user's contribution to the interference affecting the ith user's signal, σ_i^2 is the receiver noise (background noise) within the user's bandwidth received at the base station, and the sum is over the indices of the interfering mobiles. (Without loss of generality we number the mobiles from 1 through N.) The goal in the power control of wireless systems is that every mobile has the SIR above a certain target value, that is

$$\gamma_i \geq \gamma_i^{tar}, \quad \forall i = 1, \ldots, N, \tag{2}$$

The modern approach to power control for wireless systems originated in the works of Zander[36], [37] and his coworkers Grandhi *et al.*[10], [11], [12] and Foschini and Miljanic[8]. Open-loop power control has been employed to combat path loss and shadow fading[31]. The average power control technique of Gilhousen *et al.*[9], Viterbi *et al.*[32] keeps the local mean received power to a constant value, which mitigates the effect of shadowing and near-far problems. In the IS-95B and CDMA2000 standards, fast closed-loop power control is proposed to fight medium to fast fading. In Ariyavisitakul and Chang[1] and Ariyavisitakul[2], it is shown that when the power control rate is higher, it can partially accommodate the effect of fast fading. Several closed-loop power algorithms proposed in [7] have the ability to compensate for the time-varying channel. In Herdtner and Chong[17] a simple distributed power control scheme with the corresponding convergence condition was given. Song *et al.*[27], [28] and Gunnarsson *et al.*[13],[14] have considered up/down power control and closed-loop power control with other nonlinear elements within the framework of nonlinear control systems. Song *et al.*[27], [28] gave guidelines for choosing the appropriate power control step size in IS-95. In Gunnarsson *et al.*[13], PID controllers were designed to overcome the effects of time-delay in the feedback loop. Koskie and Gajic[19] have formulated and solved the power update problem in CDMA using a Nash Game approach.

SIR-based power control schemes can be centralized, Zander[36], [37] and Grandhi *et al.*[10] or distributed, Zander[37], Grandhi *et al.*[11], [12], Foschini and Miljanic[8], Yates[34]. A centralized controller has information (e.g., all the link gains are known) about each user data and it provides control actions for all users. On the other hand, a distributed controller uses only local information to find a rational control action for a local user. For example, Zander[37], Grandhi *et al.*[11], Foschini and Miljanic[8] only need the user's own SIR information to calculate the

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local user's power. The distributed power control algorithm by Foschini and Miljanic[8] was shown to converge either synchronously, Foschini and Miljanic[8], or asynchronously, Mitra[22]. A framework for convergence of the generalized uplink power control was proposed by Yates[34], see also [18]. A stochastic version of the distributed power control algorithm under the assumption that the receiver (background) noise is Gaussian is considered in Ulukus and Yates[29]. Wu[33] extended Zander's problem formulation to CDMA systems by reordering the number of users in different cells. A distributed power control algorithm with active link protection has been recently studied in Bambos *et al.*[4]. In Jantti and Kim[15], a numerical linear algebra technique based on the use of the successive overrelaxation technique[30] is proposed to speed up distributed power control algorithms.

The idea of quick online estimation of link quality was initiated in Bambos[3]. Leung[20] proposed a power control scheme for TDMA data service based on the Kalman filtering technique. The Kalman filter is used for integrated power control and adaptive modulation coding in wireless packet-switched networks in Leung and Wang[21]. In Choe *et al.*[6], a linear prediction of received power is made at the base station to predict the power control bit one step ahead. Both approaches assume that the interference is Gaussian. In Qian[23] and Qian and Gajic[24], an optimization approach via the use of an estimator has been employed to solve the mobile power updates problem in wireless CDMA systems, with no assumption imposed on the stochastic nature of the interference. Qian and Gajic[25] studied the stochastic power control problem, under Gaussian white noise in the SIR measurements, via a joint power and SIR error variance minimization technique.

II. Mobile Power Updates via Iterations

In the deterministic approach to the power control problem, it is assumed that the σ_i^2 are constant known quantities, usually very small. Assuming equalities in (2) and the knowledge of all gains , then (1) represents a system of linear algebraic equations of the form

$$Ap = b, \quad p = [p_1,\ p_2,\ \ldots,\ p_N]^T \tag{3}$$

with the elements of A and B given by $a_{ij} = -\gamma^{tar} g_{ij},\ i \neq j, a_{ii} = g_{ii}$ and $b_i = \sigma^2 \gamma^{tar}$. This system can be directly solved for $p_i,\ i = 1, 2, \ldots, N$, using Gaussian elimination. However, in reality mobile knows only its own link gain and has the measurement of its own SIR, $\gamma_i(k)$, at discrete-time instants, $k = 1, 2, \ldots$. It was suggested in Foschini and Miljanic[8] that equation (1) be solved using the Jacobi fixed-point iterations[30]

$$p(k+1) = (I - A)p(k) + b \tag{4}$$

which leads to the distributed algorithm

$$p_i(k+1) = \frac{\gamma_i^{tar}}{\gamma_i(k)} p_i(k), \quad i = 1, 2, \ldots, N \tag{5}$$

where

$$\gamma_i = \frac{g_{ii} p_i}{\sum_{j \neq i} g_{ij} p_j + \sigma_i^2}. \tag{6}$$

A nice feature of the algorithm presented in (5) is that current information about the mobile's own power and SIR suffices to update the mobile's power. The algorithm is called the DPC (distributed power control) algorithm. Assuming that the transmitted powers are constrained by

$$0 \leq p_i \leq p_i^{max}, \quad i = 1, 2, \ldots, N \tag{7}$$

then, algorithm (5) can be appropriately modified into[12], [34]

$$p_i(k+1) = \min\left\{ \frac{\gamma_i^{tar}}{\gamma_i(k)} p_i(k), p_i^{max} \right\}, \quad i = 1, 2, \ldots, N. \tag{8}$$

Convergence properties of this algorithm were studied in Yates[34]. Algorithm (8) is called DCPC (distributed constrained power control). Since (5) is a fixed-point algorithm, it usually has slow convergence to the solution sought. Note that the fixed-point algorithms, in general, have a linear rate of convergence. Jantti and Kim[15] using the successive overrelaxation techniques[30], [35], proposed the second-order iterative techniques called USOPC (unconstrained second-order power control) and CSOPC (constrained second-order power control). These algorithms are given by

$$p_i^U(k+1) = \omega \frac{\gamma_i^{tar}}{\gamma_i(k)} p_i^U(k) + (1-\omega) p_i^U(k-1), \quad i = 1, 2, \ldots, N \tag{9}$$

and

$$\begin{aligned} p_i(k+1) \quad &= \quad \min\left\{ p_i^{max}, \max\left\{0, p_i^U(k+1)\right\}\right\}, \\ &\qquad i = 1, 2, \ldots, N \end{aligned} \tag{10}$$

respectively. In (9) and (10) ω is a relaxation parameter that has to be appropriately determined (in each iteration step of (10). It is known from[30] and [35] that the successive overrelaxation methods converge faster than the methods based on Jacobi iterations.

III. Steffensen Iteration Power Updates

In numerical analysis, a variety of acceleration techniques exists to speed up the convergence of fixed-point algorithms. The acceleration technique called Aitken's Δ^2 process applied to a linearly convergent fixed-point iterations leads to the procedure known as the Steffensen method, (Burden *et al.*[5] p. 50-53). The Steffensen method produces quadratic convergence of the corresponding fixed-point algorithm. In the following, under the assumption that the actual (measured) SIRs are known ($\gamma_i(k)$ is known for every k), we derive the accelerated version of the DPC algorithm using the Steffensen method. In that direction, we first present the Steffensen method and then apply it to the to power control algorithm.

Assume that we have a linearly convergent fixed-point sequence defined by $x(k+1) = f(x(k))$. This sequence is accelerated by using the Steffensen method as follows.

Steffensen Method

Step 1 Start with some initial guess x_0.

Step 2 Starting with the initial guess x_0 from Step 1 or 5, perform two iterations on the original fixed-point sequence; that is, find $x_1 = f(x_0)$ and $x_2 = f(x_1)$.

Step 3 Evaluate a Steffensen iteration using the formula

$$x_k^s = x_0 - \frac{(x_1 - x_0)^2}{x_2 - 2x_1 + x_0}, \quad k = 1, 2, \ldots \tag{11}$$

Step 4 If $|x_k^s - x_0| < \epsilon$, where ϵ is the desired tolerance, stop; the result has been obtained.

Step 5 Set $x_0 = x_k^s$, increment k by one, and go back to Step 2.

It should be observed that the Steffensen method accelerates the convergence of the original sequence by evaluating (inserting) the Steffensen iteration (which looks like that obtained from a Newton-type algorithm) after each two iterations of the original fixed-point recursion. A sequence obtained using the Steffensen method may have the quadratic rate of convergence (see Theorem 2.11, Burden *et al.*[5]). The Steffensen method applied to (5) produces the following algorithm.

Algorithm 1: Accelerated DPC via Steffensen Iterations

Step 1 Start with an initial ($k = 0$) mobile power vector. A natural choice is given by

$$p_i^{J,0}(0) = \gamma_i^{tar}\sigma^2/g_{ii}, \tag{12}$$

due to the diagonal dominance of the matrix.

Step 2 Given the initial guess $p_i^{J,0}(k)$ for the kth iteration, perform two Jacobi iterations using (5), that is, find $p_i^{J,1}(k)$ and $p_i^{J,2}(k)$ for each mobile $i = 1, 2, \ldots, N$.

Step 3 Perform the Steffensen iteration using the following formula

$$p_i^s(k+1) = p_i^{J,0}(k) - \frac{\left(p_i^{J,1}(k) - p_i^{J,0}(k)\right)^2}{p_i^{J,2}(k) - 2p_i^{J,1}(k) + p_i^{J,0}(k)}, \quad i = 1, 2, \ldots, N. \tag{13}$$

Step 4 If $|p_i^s(k) - p_i^{J,0}(k)| < \epsilon$ stop, where ϵ is the desired tolerance.

Step 5 Set $p_i^J(0) = p_i^s(k), i = 1, 2, \ldots, N$. Increment k by one and go to Step 2.

The constrained power updates can be obtained by slightly modifying Algorithm 1 to impose the constraint

$$0 \le p_i^s(k) \le p_i^{max}, \forall k = 0, 1, \ldots, \quad \forall i = 1, 2, \ldots, N \tag{14}$$

The convergence proof of the constrained Steffensen iterations should be done along the lines of Yates[34] and Huang and Yates[18], which in addition might require a restart with two Jacobi iterations when the solution hits the boundary.

IV. Numerical Example

A. Interference Model

We have considered the uplink for a single cell CDMA system with N users, where we designated the transmitted power and SIR for the ith user by p_i and γ_i, respectively. We denoted the background (receiver) noise power within the user's bandwidth by σ_i^2 where in the deterministic formulation of the power control problem for wireless networks, the noise power is treated as constant. We are using a "snapshot" model, assuming that link gains evolve slowly with respect to the SIR evolution. In this problem formulation, the SIR of the ith mobile is

$$\gamma_i = \frac{h_i p_i}{\sum_{j \ne i} h_j p_j c_{ij} + \eta_i} \tag{15}$$

where h_i is the attenuation from the ith mobile to the base station and c_{ij} is the code correlation coefficient. The code correlation coefficient c_{ij} is computed from the signatures $\mathbf{s_i}$ and $\mathbf{s_j}$ to be $c_{ij} = (\mathbf{s_j}^T\mathbf{s_i})^2$. The attenuation is calculated from the distance r_i between the mobile and base station to be $h_i = A/r_i^\alpha$ in the absence of shadow and fast fading. A is a constant gain and α is usually between 3 and 6. We will provide realistic values for these constants in the simulation section, Subsection B.

We note that this model is consistent with the general power control problem for wireless communication systems in which the SIR of mobile i is given by

$$\gamma_i = \frac{g_{ii}p_i}{I_i(\mathbf{p_{-i}})} = \frac{g_{ii}p_i}{\sum_{j \ne i} g_{ij}p_j + \sigma_i^2} \tag{16}$$

with the interference given by

$$I_i := \sum_{j \ne i} g_{ij}p_j + \sigma_i^2. \tag{17}$$

Comparing (15) and (16), we see that for CDMA uplink power control,

$$g_{ij} := \begin{cases} h_i & j = i \\ h_j(\mathbf{s_j}^T\mathbf{s_i})^2 & \text{otherwise} \end{cases} \tag{18}$$

so g_{ij} denotes an effective link gain from the jth user to the base station that specifies the jth user's contribution to the interference affecting the signal of the ith user. We will also define an effective gain matrix $\mathbf{G}$ having (i, j)th element g_{ij}.

B. Simulation Parameters

We considered a 2 km square cell with base station centered at the origin and mobile locations were chosen randomly from a uniform distribution[1]. A typical cell is shown

[1]Realistic values for this simulation example were provided by Dr. Larry Greenstein, formerly of AT&T Bell Laboratory and currently at WINLAB, Rutgers University.

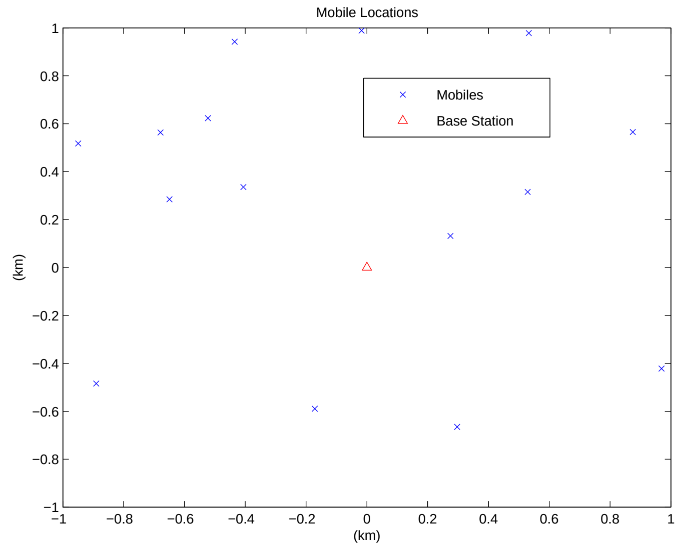

Fig. 1. A typical random distribution of 10 mobiles

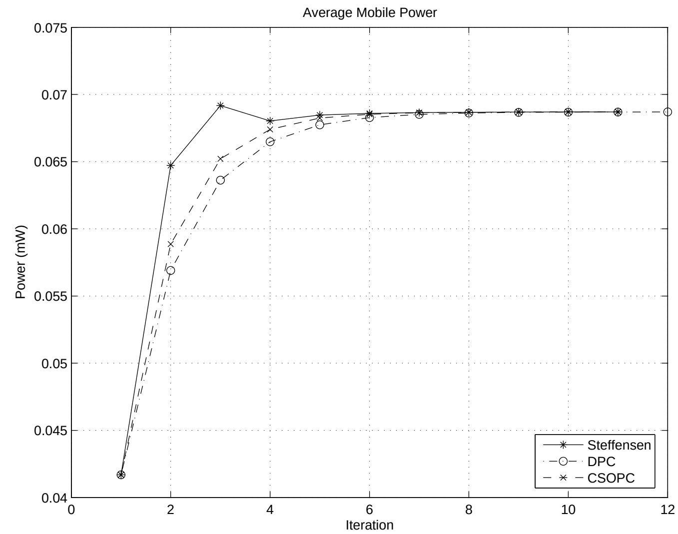

Fig. 2. Performance comparison of average powers calculated using DPC, accelerated DPC, and CSOPC in a CDMA cell with 10 users with $\gamma_i^{tar} = 5.0$ (7 dB) for all mobiles

in Figure 1. Power was limited to 600 mW corresponding to the legal limit in the US. Background receiver noise power within the user's bandwidth of $\sigma_i^2 = 2 \times 10^{-13}$ mW was used in the simulations. The channel gain was determined according to

$$h_i = \frac{A}{r^{\alpha}} \tag{19}$$

where r is the distance from the ith mobile to the base station $\alpha = 4$, and $A = 10^{-11}$, corresponding to a path loss of 110 dB at a distance of 1 km. We used random spreading sequences of length 128. We ignored fast fading and shadow fading, and interference from adjacent cells. The target SIR for all mobiles was 5, corresponding to 7 dB, although the method does not require a uniform target SIR.

C. Simulation Results

To illustrate the advantages of the proposed accelerated algorithm, we compare the results for DPC, DPC accelerated by the Steffensen method, and CSOPC power control algorithms. Since admission control is not the subject of our study, we have not implemented any call-dropping algorithm for dropping mobiles whose target SIR cannot be achieved. For the same reason, we have not investigated the effects of changing code length or target SIR.

We used ten mobiles whose locations were chosen uniformly at random within the cell. The locations were shown in Figure 1. The power for all mobiles and all algorithms was initialized to $p_i(0) = \gamma_i^{tar}\sigma^2/g_{ii}$ as proposed above in (12). Plots containing traces for all ten mobiles being difficult to read, we have arbitrarily selected the first mobile for display purposes. The average powers resulting for the three algorithms are shown in Figure 2 while the average SIRs are shown in Figure 3. Results for a typical individual mobile are shown in Figures 4 5. It can be seen from Figures 3 and 5 that the Steffensen iteration algorithm achieves the feasibility condition (2), $\gamma_i \geq \gamma^{tar}$, faster than the other two algorithms.

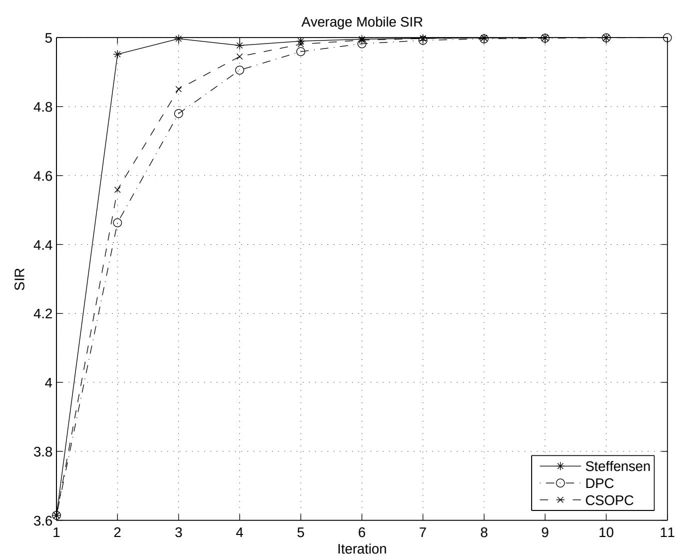

Fig. 3. Performance comparison of resulting average SIRs for DPC, accelerated DPC, and CSOPC in a CDMA cell with 10 users with $\gamma_i^{tar} = 5.0$ (7 dB) for all mobiles

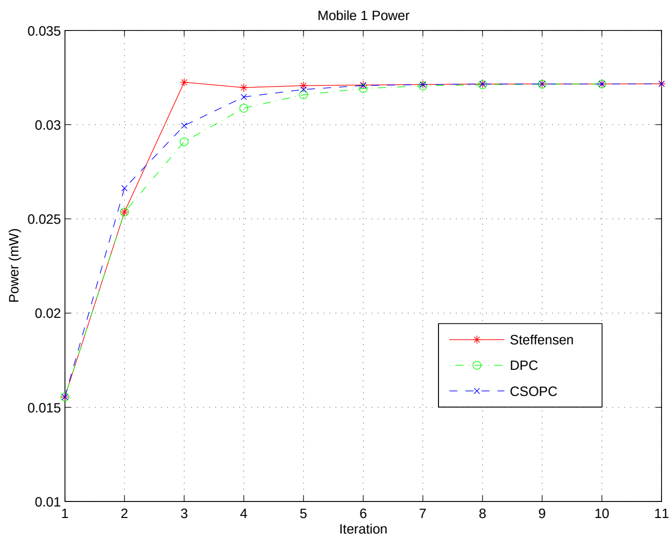

Fig. 4. Performance comparison of powers calculated using DPC, accelerated DPC, and CSOPC for a typical mobile (mobile 1) in a CDMA cell with 10 users with $\gamma_i^{tar} = 5.0$ (7 dB) for all mobiles

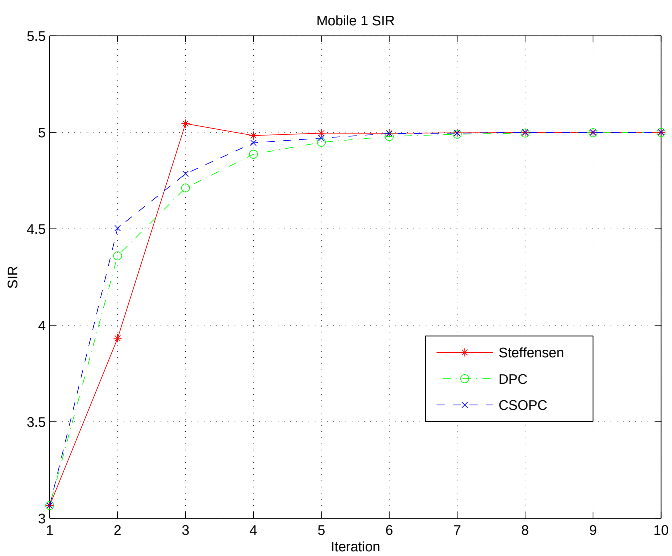

Fig. 5. Performance comparison of resulting SIRs for DPC, accelerated DPC, and CSOPC for a typical mobile (mobile 1) in a CDMA cell with 10 users with $\gamma_i^{tar} = 5.0$ (7 dB) for all mobiles

V. Conclusions

An algorithm that accelerates the DPC algorithm has presented and its performance demonstrated in simulation. Further studies of the proposed algorithm with respect to its well conditioning and numerical stability are needed, which should be the case with any numerical algorithm used in engineering applications. The extension of the presented results to USOPC and the constrained versions of the DPC and USOPC algorithms is underway by the authors.

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