Optimal SIR-Based Power Updates in Wireless CDMA Communication Systems

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***Abstract*— In this paper we present two new control algorithms that potentially can be used as efficient techniques for power updates in wireless CDMA communication networks. The algorithms are obtained by optimizing the signal-to-interference error. The control laws are distributed, respectively linear and bilinear, and require either estimation of the channel interference (or a quantity inversely proportional to the signal interference) or the development of efficient numerical algorithms for solving the set of algebraic equations obtained. In addition, ideas of how to accelerate the convergence of a Nash game power control algorithm are presented.**

I. INTRODUCTION

The modern approach to power control for wireless systems originated in the works of Zander (1992a,b) and his coworkers Grandhi et al. (1993, 1994, 1995), Grandhi and Zander (1994), as well as in the often cited paper by Foschini and Miljanic (1993).

The SIR based power control schemes can be centralized, Zander (1992a,b) and Grandhi et al. (1993) or distributed, Zander (1992b), Grandhi et al. (1994, 1995), Foschini and Miljanic (1993), Yates (1995). A centralized controller has information (e.g., all the link gains are known) about each user 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. The distributed power control algorithm by Foschini and Miljanic (1993) was shown to converge either synchronously, Foschini and Miljanic (1993), or asynchronously, Mitra (1994). A framework for convergence of the generalized uplink power control was proposed by Yates (1995), see also Huang and Yates (1998). A distributed power control algorithm with active link protection has been recently studied by Bambos et al. (2000). In Jantti and Kim (2000), a numerical linear algebra technique based on the use of the successive overrelaxation technique (Varga, 2000) is proposed to speed up distributed power control algorithms.

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In the IS-95B and CDMA2000 standards, fast closed-loop power control is proposed to fight medium to fast fading. In Ariyavisitakul and Chang (1993) and Ariyavisitakul (1994), it is shown that a higher power control rate can partially accommodate the effect of fast fading. Several closed-loop power algorithms proposed in Chockalingam et al. (1998) have the ability to compensate for the time-varying channel characteristics. In Herdtner and Chong (2000) a simple asynchronous distributed power control scheme based on the schemes used in IS-95 with the corresponding convergence condition was given. Song et al. (1999, 2001) and Gunnarson et al. (1999a,b) 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. (1999, 2001) gave guidelines for choosing the appropriate power control step size in IS-95. In Gunnarson et al. (1999a), PID controllers were designed to overcome the effects of time-delay in the feedback loop.

Ulukus and Yates (1998) studied the stochastic power control problem formulation using match filters and the Gaussian white noise assumption. The idea of quick online estimation of link quality was initiated by Bambos (1998). Leung (1999) 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 (2000). In Choe et al. (1999), 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 (2001) and Qian and Gajic (2003), an optimization approach using an estimator has been employed to solve the stochastic mobile power update problem in wireless CDMA systems, with no assumption imposed on the stochastic nature of the interference.

A utility based power control and pricing was considered by Ji and Huang (1998), Sarayadar et al., (2001, 2002), Alpcan et al., (2002), and Xiao et al. (2003).

II. ITERATIVE METHODS FOR SIR-BASED POWER CONTROL IN WIRELESS NETWORKS

Consider the uplink (mobile-to-base) power control problem with N active users in a CDMA wireless system. As is customary in the recent literature, it is assumed that noise is negligible and therefore the signal to interference ratio is defined by:

$$\gamma_i = \frac{g_{ii}p_i}{\sum_{j=1,j\neq i}^{n} g_{ij}p_j} = \frac{g_{ii}p_i}{I_i(\mathbf{p}_{-i})}, \quad i = 1,2,\ldots,n \tag{1}$$

where p_i is the transmission power for user i, g_{ij} is the link gain from mobile station j to base station i, and σ_i is receiver noise (background noise) at base station i. $I_i(\mathbf{p}_{-i})$ in (1) denotes the interference power for mobile i, where $\mathbf{p}_{-i}$ indicates that the power of mobile i is not present in the interference it experiences.

The goal in the power control of wireless systems is that every mobile has SIR above a certain target value

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

In the deterministic approach to the power control problem defined in (1)–(2), it is assumed that the σ_i are constant, known, usually very small quantities. In the stochastic approach to the power control problem in wireless networks, it will be assumed that network noise is a stochastic process. Assuming equalities in (2) and knowledge of all gains g_{ij}, (1) represents a system of linear algebraic equations of the form

$$A\mathbf{p} = \mathbf{b}, \quad \mathbf{p} = [p_1, p_2, \ldots, p_n]^T \tag{3}$$

with the elements of $\mathbf{A}$ and $\mathbf{b}$ given by $a_{ij} = -\gamma_i^{tar} g_{ij}/g_{ii}, i \neq j$, $a_{ii} = 1$, and $b_i = \sigma_i^2 \gamma_i^{tar}/g_{ii}$. This system can be directly solved for the $p_i, i = 1,2,\ldots,n$, using, for example, the Gaussian elimination method. However, in reality (in the currently implemented IS-95 power control mechanism) mobile i knows only its own SIR, $\gamma_i(k)$, at discrete-time instants, $k = 0,1,2,\ldots$. It is interesting to observe that the iterative methods for solving systems of linear algebraic equations (Varga, 2000) can produce the solution of (3) with the knowledge of $\gamma_i(k)$ and γ_i^{tar} only. That observation led to the development of several iterative techniques for power control of wireless networks.

Foschini and Miljanic (1993) suggested solving equation (3) using the following iterations

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

where

$$a_{ii} = 1, \quad a_{ij} = -\gamma_i^{tar}\frac{g_{ij}}{g_{ii}}, \quad b_i = \gamma_i^{tar}\frac{\sigma_i^2}{g_{ii}}. \tag{5}$$

It can be easily shown that (4) represents Jacobi iterations, a technique used for iterative solution of linear systems of algebraic equations (Varga, 2000). The Jacobi iterations (4) can be represented as the following distributed algorithm

$$p_i(k+1) = \frac{\gamma_i^{tar}(k)}{\gamma_i(k)} p_i(k), \quad i = 1,2,\ldots,n \tag{6}$$

where

$$\begin{aligned} \gamma_i(k) &= \frac{g_{ii}p_i(k)}{\sum_{j=1,j\neq i}^{n} g_{ij}p_j(k) + \sigma_i^2} = \frac{g_{ii}p_i(k)}{I_i(\mathbf{p}_{-i}(k))}, \\ &= \delta_i(k)p_i(k). \end{aligned} \tag{7}$$

The quantity $\delta_i(k)$ is called the channel variation. According to (7), the channel variation is defined by

$$\delta_i(k) = \frac{g_{ii}}{I_i(\mathbf{p}_{-i}(k))} = \frac{\gamma_i(k)}{p_i(k)}. \tag{8}$$

Note that in the currently implemented IS-95 power update scheme, the signal $\gamma_i(k)$ is measured on line. The algorithm defined in (6) can be derived from (4)–(5) by multiplying the matrix and the vector in (4) and eliminating the interference using (7).

It is interesting to observe that algorithm (4) is derived by using a completely different approach than had been used previously. Namely, Foschini and Miljanic (1993) assigned power evolution dynamics so that the steady state value of a dynamic system (described either by differential or difference equation) represents the solution of $\mathbf{Ax} = \mathbf{b}$.

The result established by Foschini and Miljanic, (1993) can also be achieved using the following differential, respectively, difference equations to model power dynamics

$$\begin{aligned} \frac{d\mathbf{p}(t)}{dt} &= -\alpha\left(\mathbf{A}\mathbf{p} - \mathbf{b}\right), \\ \mathbf{p}(k+1) &= \left(\mathbf{I} - \beta\mathbf{A}\right)\mathbf{p}(k) + \beta\mathbf{b}, \end{aligned} \tag{9}$$

with α being a large positive number (assuming that the matrix $\mathbf{A}$ has all eigenvalues in the right half plane, which is the case when $\mathbf{A}$ is diagonally dominant), and β chosen such that $\max|\lambda_i(\mathbf{I} - \beta\mathbf{A})| < 1$. In such cases the steady state solutions of (9), given by

$$\begin{aligned} 0 = -\alpha\left(\mathbf{A}\mathbf{p}_{ss} - \mathbf{b}\right) \quad &\Rightarrow \quad \mathbf{A}\mathbf{p}_{ss} = \mathbf{b} \\ \mathbf{p}_{ss} = \left(\mathbf{I} - \beta\mathbf{A}\right)\mathbf{p}_{ss} + \beta\mathbf{b} \quad &\Rightarrow \quad \mathbf{A}\mathbf{p}_{ss} = \mathbf{b} \end{aligned} \tag{10}$$

satisfy (3) and represent the required solution to the power control problem. Foschini and Miljanic (1993) derived the first formula in (9) by using a "surrogate" derivative, which is unnecessary. For $\beta = 1$, the second formula in (9) represents (3), and leads to the DPC algorithm (6)–(7).

III. NEW ALGORITHMS FOR MOBILE POWER UPDATES

In this section we present two new algorithms for iterative power updates in wireless communication networks. Our motivation comes from the power control results for wireless networks obtained recently by Qian and Gajic (2003) where the following power updates algorithms was considered

$$p_i(k+1) = p_i(k) + \alpha_i(k)e_i(k), \quad i = 1,2,\ldots n$$

where $e_i(k)$ is the SIR error defined by

$$e_i(k) = \gamma_i^{tar} - \gamma_i(k), \quad i = 1,2,\ldots n \tag{11}$$

and $\alpha_i(k)$ is a gain obtained through an optimization process, which depends on the estimated and predicted values of the channel variation defined in (8).

Here, we present new and simple variants of the mobile power updates algorithm of Qian and Gajic (2003).

Algorithm 1: (Linear and Additive Power Updates) The mobile power can be updated according to the following distributive linear control law

$$p_i(k+1) = p_i(k) + u_i(k), \quad i = 1, 2, \ldots n \tag{12}$$

where the control variable $u_i(k)$ has to be chosen such that the square of the SIR error is minimized in the discrete time instant $k+1$, that is

$$\min_{u_i(k)} \left\{ e_i^2(k+1) \right\}. \tag{13}$$

The necessary condition for minimum of (13), together with definitions (8), (11), and (12) imply

$$\begin{aligned}
\frac{\partial \left(e_i(k+1)\right)^2}{\partial u_i} &= \frac{\partial \left(\gamma_i^{tar} - \gamma_i(k+1)\right)^2}{\partial u_i} \\
&= \frac{\partial \left(\gamma_i^{tar} - \delta_i(k+1)p_i(k+1)\right)^2}{\partial u_i} \\
&= \frac{\partial \left(\gamma_i^{tar} - \delta_i(k+1)(p_i(k) + u_i(k))\right)^2}{\partial u_i} \\
&= -2\delta_i(k+1)(\gamma_i^{tar} - \delta_i(k+1)(p_i(k) + u_i(k))) \\
&= 0
\end{aligned}$$

which leads to the following optimal solution

$$\begin{aligned}
u_i^*(k) &= \frac{\gamma_i^{tar}}{\delta_i^*(k+1)} - p_i^*(k) = \frac{\gamma_i^{tar}}{\delta_i^*(k+1)} - \frac{\gamma_i^*}{\delta_i^*(k)} \\
& \quad i = 1, 2, \ldots n
\end{aligned} \tag{14}$$

with

$$\delta_i^*(k+1) = \frac{g_{ii} p_i^*}{I_i(\mathbf{p}_{-i}^*(k+1))} = \frac{\gamma_i^*(k+1)}{p_i^*(k+1)} = \frac{\gamma_i^{tar}}{p_i^*(k+1)}. \tag{15}$$

The optimal solution given in terms of the channel interference is

$$\begin{aligned}
u_i^*(k) &= \frac{1}{g_{ii}} \left(\gamma_i^{tar} I_i(\mathbf{p}_{-i}^*(k+1)) - \gamma_i^*(k) I_i(\mathbf{p}_{-i}^*(k)) \right) \\
&= \frac{1}{g_{ii}} \gamma_i^{tar} I_i(\mathbf{p}_{-i}^*(k+1)) - p_i^*(k).
\end{aligned} \tag{16}$$

The corresponding optimized power updates are given by

$$\begin{aligned}
p_i^*(k+1) &= p_i^*(k) + u_i^*(k), \\
&= \frac{\gamma_i^{tar}}{g_{ii}} I_i(\mathbf{p}_{-i}^*(k+1)), \quad i = 1, 2, \ldots n
\end{aligned} \tag{17}$$

or using (8)

$$p_i^*(k) = \frac{\gamma_i^{tar}}{g_{ii}} I_i(\mathbf{p}_{-i}^*(k)) = \frac{\gamma_i^{tar}}{\delta_i^*(k)}, \quad i = 1, 2, \ldots n. \tag{18}$$

Note that since

$$\begin{aligned}
\{e_i^*(k+1)\}^2 &= \left(\gamma_i^{tar} - \delta_i^*(k+1)(p_i^*(k) + u_i^*(k))\right)^2 \\
&= \left(\gamma_i^{tar} - \delta_i^*(k+1)p_i^*(k) - \gamma_i^{tar} + \delta_i^*(k+1)p_i^*(k)\right)^2 \\
&= 0
\end{aligned}$$

the result obtained in (14) also represents the sufficient condition for minimization of the defined cost function

$$e_i^2(k+1) \geq 0.$$

It should be emphasized that the error cost can theoretically be reduced instantaneously to zero, assuming that the channel interference (or channel variation) is exactly known. In practice, an estimator (observer) is needed to estimate the channel interference, which will require several iterations (power updates) before the error settles down to zero. The use of an estimator to estimate the channel variation is considered in Qian (2001); Qian and Gajic (2003). The use of an estimator to estimate the interference in a mobile channel was considered by several researchers, for example Leung and Wang (2000); Leung, (1999, 2002). In practice, using an estimator, the optimal mobile power updates obtained in (18) could be implemented as

$$p_i^*(k) = \frac{\gamma_i^{tar}}{g_{ii}} I_i^{est}(\mathbf{p}_{-i}^*(k)), \quad i = 1, 2, \ldots n \tag{19}$$

or

$$p_i^*(k) = \frac{\gamma_i^{tar}}{\delta_i^{est}(k)}, \quad i = 1, 2, \ldots n \tag{20}$$

where $I_i^{est}(\mathbf{p}_{-i}^*(k))$ and $\delta_i^{est}(k)$ are, respectively, the estimated values for the channel interference and the channel variation. The accuracy of the estimates of the channel interference or channel variation directly determine the accuracy of the optimal powers. However, since in practice the gains and interference change (in IS-95 the powers are updated 800 times per second), we should not aim for the exact optimal solution. Using a near-optimal solution at the given discrete-time instant is acceptable since we have to move very rapidly (hopefully not at 800 Hz) to the next time instant and generate a new estimate of the channel interference (channel variation).

In the final version of this paper, we will include a realistic example using a very simple estimator for the mobile interference.

Comment: In view of the result obtained in (18), we can notice that the fixed point algorithm for solving algebraic equations (18) is identical to the DPC algorithm defined in (6), which indicates that the solution of (18) is identical to the power balancing solution, or more precisely, that the power balancing solution is optimal in the sense that it brings the SIR error to zero (in general, after a lot of iterations). It is known that the fixed point algorithms have slow convergence. Research is underway to find more efficient algorithms for solving (18). However, in practical implementation of (18), we have a one shot solution defined by (19) or (20), depending whether an estimate of the channel interference or the channel variation is known.

Algorithm 2: (Bilinear Control Law)

The mobile power can also be updated according to the following distributive bilinear control law

$$p_i(k+1) = p_i(k) u_i(k), \quad i = 1, 2, \ldots n \tag{21}$$

where $u_i(k)$ is the control variable. Using the same cost function as the one defined in (13), the necessary conditions imply the following solution

$$u_i^*(k) = \frac{\gamma_i^{tar}}{g_{ii}p_i^*(k)} I_i(\mathbf{p}_{-i}^*(k+1)). \tag{22}$$

The corresponding optimized power updates are given by

$$\begin{aligned} p_i^*(k+1) &= p_i^*(k)u_i^*(k) \\ &= \frac{\gamma_i^{tar}}{g_{ii}} I_i(\mathbf{p}_{-i}^*(k+1)), \\ & \quad i = 1, 2, \ldots n \end{aligned} \tag{23}$$

or using (8)

$$p_i^*(k) = \frac{\gamma_i^{tar}}{g_{ii}} I_i(\mathbf{p}_{-i}^*(k)) = \frac{\gamma_i^{tar}}{\delta_i^*(k)}, \quad i = 1, 2, \ldots n \tag{24}$$

which identical to (18) — the result obtained for the linear (additive) power updates. Hence, in this problem formulation, both linear and bilinear control laws produce the same optimal power update algorithm. This result is interesting from both theoretical and practical points of view. It is theoretically known that we can achieve more with multiplicative control than with additive control, however, in our problem formulation they happened to produce the same power update algorithm. Practically, the additive control law (12) is much simpler for implementation that the multiplicative control law (21).

IV. ACCELERATION OF A NASH GAME POWER CONTROL ALGORITHM

In this section we indicate that the Nash game power control algorithm of Koskie (2003) and its accelerated version of Gajic and Koskie (2003) can be further improved by using the third-order Newton algorithm for iterative solution of the corresponding power update equations. Namely, it has been shown recently that the Newton algorithm for solving systems of algebraic equations can produce the third-order of accuracy Weerakoon and Fernando (2000), M. Palacios (2002), and A. Ozban (2004).

It is well known that for a nonlinear algebraic equation of the form

$$f(x) = 0 \tag{25}$$

the Newton algorithm, defined by

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)}, \quad k = 0, 1, 2, \ldots \tag{26}$$

with the initial condition x_0 being sufficiently close to the exact solution, has quadratic rate of convergence. Weerakoon and Fernando (2000) derived the third-order variant of the Newton method as

$$x_{k+1} = x_k - \frac{2f(x_k)}{f'(x_k) + f'(z_{k+1})}, \quad k = 0, 1, 2, \ldots \tag{27}$$

where

$$z_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)}, \quad k = 0, 1, 2, \ldots \tag{28}$$

This algorithm is called by Ozban (2004) the arithmetic mean 3rd-order Newton method. In Ozban (2004), two addition third-order Newton algorithms were derived, namely the harmonic mean 3rd-order Newton algorithm defined by

$$x_{k+1} = x_k - \frac{f(x_k)\left[f'(x_k) + f'(z_{k+1})\right]}{2f'(x_k)f'(z_{k+1})}, \quad k = 0, 1, 2, \ldots \tag{29}$$

with z_{k+1} given by (27), and the midpoint 3rd-order Newton method defined by

$$x_{k+1} = x_k - \frac{f(x_k)}{f'((x_k + z_{k+1})/2)}, \quad k = 0, 1, 2, \ldots \tag{30}$$

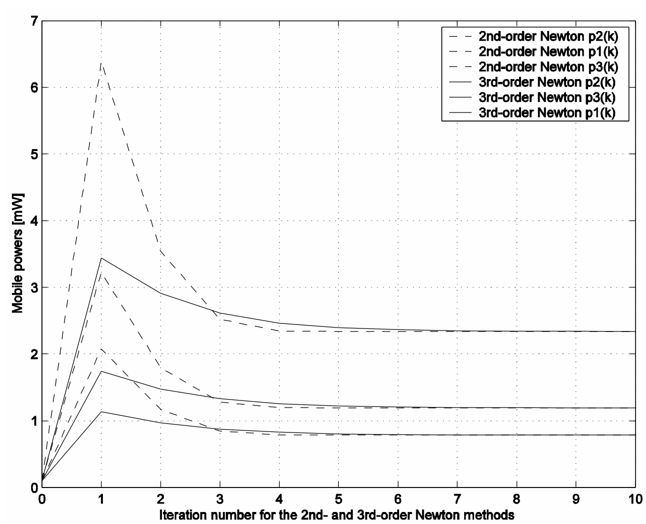
According to the problem formulation of Koskie (2003), the Nash equilibrium mobile powers satisfy

$$\begin{aligned} \mathbf{F}_i(\mathbf{p}, \mathbf{g}_i, \sigma_i) &= 0 \\ &= p_i - \frac{\gamma_i^{tar}}{g_{ii}} \left(\sum_{j=1, j\neq i}^{n} g_{ij}p_j + \sigma_i^2 \right) + \\ & \quad \frac{1}{2g_{ii}^2} \left(\sum_{j=1, j\neq i}^{n} g_{ij}p_j + \sigma_i^2 \right)^2, \\ & \quad i = 1, 2, \ldots n. \end{aligned} \tag{31}$$

The vector form of the 3rd-order Newton algorithm (27) is applied to (31) using the data from the mobile power control example of Gajic and Koskie (2003). The gain matrix is given by

$$\mathbf{G} = \begin{bmatrix} 1.0000 & 0.0882 & 0.0357 \\ 0.1524 & 0.9500 & 0.3501 \\ 0.0670 & 0.0244 & 0.9900 \end{bmatrix}$$

and $\sigma_i = 0.1$, $\gamma_i^{tar} = 5$, $p_i^{(0)} = 0.1$, $i = 1, 2, 3$. The results obtained for the power updates for the 2nd- and 3rd-order Newton methods are presented in the following figure.



The superiority of the 3rd-order Newton method over the 2nd order Newton method is obvious.

V. CONCLUSIONS

We have derived the optimal additive (linear) and multiplicative (bilinear) power update laws and shown that they lead to the same algorithm. The linear power update control law is more convenient for implementation due to its simplicity. Further studies are needed to find a numerically efficient algorithm for solving the obtained set of algebraic equations (18), unless an estimator is used to estimate either channel interference or channel variation, in which case formula (18) is a one-shot optimal solution (as accurate as the estimates). In addition, we have indicated how to accelerate the Nash game mobile power distribution algorithm of Gajic and Koskie (2003).

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