Generalized Predictive Power Control Algorithms for WCDMA Systems

Rodrigo Rodrigues Sumar, Antonio Augusto R. Coelho, Carlos Aurélio F. da Rocha, Leonardo Silva Resende

Abstract - **Over the last decade, predictive control has emerged as the standard for monovariable and multivariable control systems in the process industries. Its ability to handle complex systems make it an attractive tool for many challenging tasks. In this paper, the design of the non-constrained and constrained generalized predictive controllers is reviewed and assessed to control the up-link power on a WCDMA system. Simulation results are shown not only to evidence that a replace from bang-bang to predictive technologies can be an efficient manner in power command but also to illustrate that the effects of radio channel loss of the system can be over-compensated.**

Keywords – **signal-to-noise ratio, power command, predictive controller, WCDMA, constraints.**

I. INTRODUCTION

Power control in Code-Division Multiple Access (CDMA) systems is an essential radio resource function to provide quality of service in cellular communication systems [3], [4], [5], [6], [7]. In conventional IS-95 CDMA systems, bang-bang control is employed for the power control. If there are radio channel variations (stochastic nature of the link, interference), the bang-bang solution can deteriorate the quality level of the received signal switching the power control input alternately from one extreme to another. Another dynamic problem is that static models are considered in the bang-bang structure and, therefore, the varying nature of the CDMA system is not taken into account in the power control design [4], [5], [6].

Several attempts have been done and shown in the communication literature in order to avoid and to overcome the problems associated with incorrect power commands. In [7], the Signal-to-Interference Ratio (SIR) bang-bang control was used as a transmitter power command. Delays in the feedback loop and the rapid fading of the channel can cause an inadequate power adjustment. In [6], a fuzzy logic scheme was used as fuzzy power control algorithm. In [4] and [5], adaptive power commands were obtained by minimizing a cost function and by considering the self-tuning approach.

These previous power control solutions can be deficient for a variety of reasons:

- the total number of bits for coding the power control command is considered as a practical constraint;
- previous minimum variance power control can be considered as particular cases of the generalized predictive control algorithm;
- more insight for the operator is needed about the controlled system, which means to tune the controller in order to provide the best closed-loop performance;
- the selection of the tuning parameters of the predictive (including the minimum variance) controller for Wideband-CDMA (WCDMA) power system is still an open problem for the communication community.

This paper reviews the generalized predictive control (GPC) algorithm, including the non- and constrained (not shown in the literature) cases, in order to analyze dynamic effects, which are involved by constraints on the control signal for WCDMA systems. One of the reasons for applying GPC in the WCDMA system is the possibility of explicitly incorporating constraints in the control system design.

II. CDMA SYSTEM

A. CDMA Control System

For the purpose of the adaptive predictive power control design, consider the simplified system model described in Figure 1. The CDMA up-link closed-loop power control is used in a single-link simulation environment and it is similar to those presented in [4], [5], [7]. So, $TP(t)$ is the transmitted signal power of the mobile station at the discrete-time t, TPL_0 is the target value of power level and $RP(t)$ is the received signal power at the base station. $I(t)$ models the interference as additive white Gaussian noise (AWGN) and $G(t)$ is the single-link gain between the base station and the mobile station modeled as Rayleigh fading using the Jake's model [9]. Since the interference power in decibels is not additive, $I(t)$ is then given by [6]

$$\left\{10\,log\left[tp(t)g(t)+i(t)\right]-10\,log\left[tp(t)g(t)\right]\right\}= \\ 10\,log\left[1+\frac{i(t)}{tp(t)g(t)}\right]\ (db) \tag{1}$$

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where $rp(t) = tp(t)g(t) + i(t)$ is the received power in *Watts* and $i(t)$ is the instantaneous additive interference power. The signal $tp(t)$ is expressed in linear unit (*Watts*) and $g(t)$ is dimensionless, so they are corresponding to $TP(t)$ and $G(t)$ expressed in *dB*. In all numerical simulations of the single-link case, the carrier frequency is *1800MHz* and the speed of the mobile is *1.4m/s*. The power control command, $u(t) \in \{-1,1\}$, is determined from the received power at the base station. The base station increases or decreases its transmitted power by a prescribed fixed amount Δ according to the binary value of $u(t)$. The power control command $u(t)$ is not protected under the fast fading, and thus is subject to down-link channel error.

III. GENERALIZED |PREDICTIVE POWER CONTROLLER

Design characteristics of the predictive control are: i) it can provide a good closed-loop behavior for complex processes, ii) it can be easily understood and formulated, and iii) it can accommodate constraints in the system signals. Predictive controllers are implemented by solving an optimization problem in order to find future control signals to minimize the cost function [1], [8]

$$J(N_y,N_u) = \sum_{j=N_1}^{Ny} [y_r(t+j) - y(t+j/t)]^2 + \Lambda \sum_{j=0}^{Nu} [u(t+j)]^2 \qquad (2)$$

where $\{y_r(t+j)\}$ are future values of the reference (target power level), $\{y(t+j/t)\}$ are future values of the predicted output (received power), $\{u(t+j)\}$ is the sequence of future control signals (transmitted power command), Λ is the control weighting that penalizes the control energy and parameters N_1, Ny, Nu are initial, output and input horizons, respectively. GPC design is based on the equations

$$R(z^{-1})u(t) + S(z^{-1})y(t) + T(z^{-1})y_r(t) = 0 \qquad (3)$$

$$R(z^{-1}) = \left[1 + z^{-1} \sum_{j=N_1}^{Ny} k_j \Gamma_j(z^{-1})\right]$$

$$S(z^{-1}) = \left[\sum_{j=N_1}^{Ny} k_j F_j(z^{-1})\right] \quad , \quad T(z^{-1}) = -\left[\sum_{j=N_1}^{Ny} k_j z^j\right]$$

where design operators $F_j(z^{-1})$, $\Gamma_j(z^{-1})$ and coefficients of k_j $[j=1,2,...,N_y]$ are obtained from the plant nominal model by using the following steps. First, it is assumed that the process (the channel including the mobile station) is modeled by

$$A(z^{-1})y(t) = z^{-1}B(z^{-1})u(t) \qquad (4)$$

To obtain the design operators of $F_j(z^{-1})$, which are polynomials of degree $n_a\text{-}1$ (n_a is the degree of the plant), it is necessary to solve the following equations

$$E_j(z^{-1})A(z^{-1}) + z^{-j}F_j(z^{-1}) = 1 \qquad (5)$$

for $j=1,2,...,Ny$ which yields the intermediate polynomial $E_j(z^{-1})$ of degree $(j\text{-}1)$. The second set of design operators, the polynomials $\Gamma_j(z^{-1})$ of degree $(nb\text{-}1)$, are obtained by decomposition the product $E_j(z^{-1})B_j(z^{-1})$ as

$$E_j(z^{-1})B(z^{-1}) = G_j(z^{-1}) + z^{-j}\Gamma_j(z^{-1}) \qquad (6)$$

where polynomials $G_j(z^{-1})$, of degree $(j - 1)$, are known as the dynamic polynomials and are characterized by the step response elements of the plant. Predictive control techniques use the assumption that there is a future instant $t+Nu$ beyond which the control will remain constant. So, the coefficients of the dynamic polynomial are used to define the non-zero elements of the Toeplitz matrix G_{Nu}, referred to as truncated dynamic matrix that contains only Nu columns. Finally, the coefficients of k_j, $j=1,2,...,N_y$ are calculated, as the components of the gain vector $K^T = [k_1\ k_2\ ...\ k_{Ny}]$, from

$$K^T = \begin{bmatrix}1 & 0 & \dots & 0\end{bmatrix}\left[G_{Nu}^T G_{Nu} + \Lambda I\right]^{-1} G_{Nu}^T \qquad (7)$$

and the control law to be applied is

$$u(t) = K(Y_r - Y^{OL}) \qquad (8)$$
$$(Y_r)^T = [y_r(t+1)\ \ y_r(t+2)\ \ ...\ \ y_r(t+Ny)]$$
$$(Y^{OL})^T = [y^{OL}(t+1)\ \ ...\ \ y^{OL}(t+Ny)]$$

The vector Y^{OL} describes how the system would respond in open-loop mode. When new measurements are available, a new optimization problem is formulated whose solution provides the new control action [1].

A. Generalized Predictive Design – Constrained Case

When addressing real applications, the problem of constraints on system's variables appears. The approach presented in this paper assumes constraints on the control signals. At each sampling period the saturation constrained GPC law minimizes the GPC cost function, with respect to the control vector u, subject to the following amplitude constraints: $u_{\min} \le u(t+j) \le u_{\max}$, where $j = 0, 1, ..., Nu$. The control law is then formulated as a quadratic programming problem defined as

$$\begin{array}{ll} \min\limits_{u} & J = u^T H u + c^T u \\ \text{subject to} & Mu \le n \end{array}$$

For details of the constrained GPC design see [1], [8]. The bang-bang control nature in WCDMA systems can be considered as a special case of a constrained problem: the control signal can take one of only two possible values. Therefore, the vector u can have only 2^{Nu} combinations, and so we can search through the 2^{Nu} possibilities to find the control vector u that minimizes the cost function. A straightforward method is an exhaustive search or, alternatively, integer programming techniques can be used to find the optimum. However, because the value of Nu is generally chosen to be small (1 to 3), integer programming techniques can not pay off considering the complexity of the algorithm; exhaustive search is therefore considered to be adequate here which minimizes the cost function.

B. Minimum Variance Design – Particular Case

Minimum variance controllers belong to the class of predictive control when the one-step-ahead philosophy is implemented [2]. So, instead of using the predictive performance criterion of the equation (2), the generalized minimum variance control law is designed to minimize the following cost function:

$$J = \left[y(t+2) - y_r(t+2) \right]^2 + \Lambda \left[u(t) \right]^2 \qquad (9)$$

where the tuning parameter Λ must be selected by the operator in order to penalize the overshoot and control effort. So, the cost function is minimized to obtain the following control law:

$$u(t) = \frac{b_0 \left\{ y_r(t+2) - a_1^2 y(t) - (b_1 - a_1 b_0) u(t-1) + a_1 b_1 u(t-2) \right\}}{(b_0{}^2 + \Lambda)} \qquad (10)$$

Clarke's controller, besides allowing reference tracking, is efficient to decrease the output and control variances when compared to the Åström's regulator [2].

C. Predictive Power Design – Adaptive Case

The power control objective is to determine *u(t)* such that the *RP(t)* follows its target value TPL_0 under channel uncertainties, as close as possible. Due to channel variations, an estimation algorithm must be coupled to the controller design in order to keep a good closed-loop performance, and so, leading to adaptive power control. The identification technique of the Recursive Least Squares (RLS) has proved to be an appropriate choice because it presents good convergence properties and computation simplicity [1], [4], [5]. The behavior of the WCDMA system is governed by a mathematical model for identification purposes as follows

$$A(z^{-1}) = 1 + a_1 z^{-1} \quad , \quad B(z^{-1}) = b_0 z^{-1} + b_1 z^{-2} \qquad (11)$$

The measured input-output data are obtained from the radio channel (single-link) simulator [4], [5]. Parameter and measurement vectors are, respectively,

$$\theta^T(t) = [a_1 \ b_0 \ b_1] \quad , \quad \varphi^T(t) = [-y(t-1) \ u(t-2) \ u(t-3)]$$

where *y(t)* is the output — received power and *u(t)* is the control — transmitter power control. A description of the RLS estimator algorithm can be reviewed in [1], [8]. The mathematical model of the equation (11) comes from a trade-off between the capacity of representation of the WCDMA system and the model simplicity [4], [5].

IV. SIMULATION RESULTS

To assess the performance of the predictive power control algorithms, some numerical essays are conducted. Results are obtained by using *100* runs and varying the signal-to-noise ratio (SNR) between simulations. SNR values of *5*, *7*, *10*, *13*, *15*, *17*, *20*, *22*, *25*, *28*, *30dB* are utilized. The standard deviation of the received power as function of SNR is evaluated and the target power level is set to $TPL_0 = 0dB$. Design parameters of the RLS algorithm are set as follows: $\lambda = 0.95$, $\theta^T(0) = [0.1 \ \ 0.1 \ \ 0.1]$, $P(0) = 5000 I_{3x3}$. In all controllers the power control signal is set to *±1dB*.

First, simulation results are compared with those obtained by using bang-bang and non-constrained generalized predictive power controllers. For the comparative study, the controller of the equation (3) is implemented and the tuning parameters are set to $N_1 = 1$, $Ny = 5$, $Nu = 2$, $\Lambda = 0.01$. Figure 2 shows that the standard deviation of the received power is smaller with generalized predictive controller than with the bang-bang controller. Next, results are given in order to show how the generalized predictive power controller implemented in non- and constrained cases, can modify the closed-loop performance of the WCDMA system. Figure 3 shows that the responses are very similar. The advantage of the constrained GPC design lies in its simplicity. Finally, the goal of this study is to compare the performance of the minimum variance and constrained generalized predictive controllers. Figure 4 shows that all two control strategies give good performance.

V. CONCLUSIONS

This paper presented a case study of self-tuning predictive power control strategies when applied to a WCDMA system. The dynamic behavior of the predictive controllers, to deal with the uncertain nature of the channel, has been shown to be more robust than the conventional bang-bang controller. Simulation studies have shown a significant reduction in the standard deviation of the received power, under various SNR values, for the three predictive power controllers. So, it is evident that the low complexity and the high accuracy of the minimum variance algorithm in the single-link case study is paving a good solution in power control.

The adaptation level presented in the adaptive predictive control strategies was based on the RLS technique, which provides an adequate power control solution for handling the uncertainty of the channel in a WCDMA system.

Further studies are expected for extending the adaptive predictive power control strategies to deal with multi-user. In addition, the generalized predictive controller with PID characteristic is under investigation in single- and multi-link cases.

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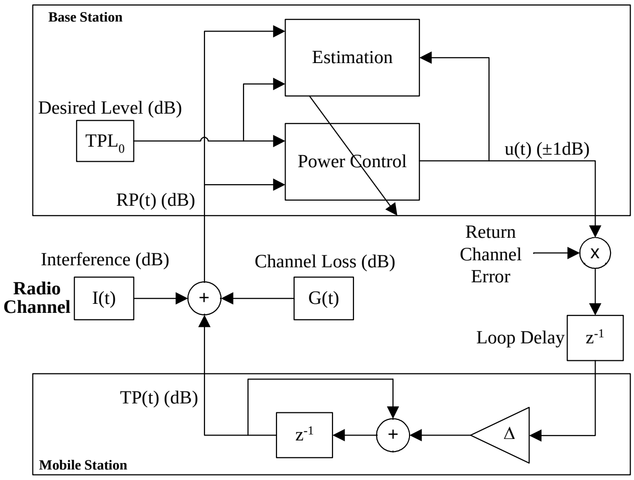

Fig. 1. Power control system model in adaptive fashion.

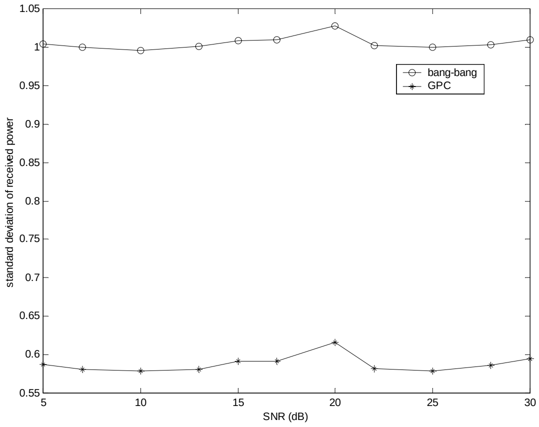

Fig. 2. Standard deviation of the received power as a function of SNR.

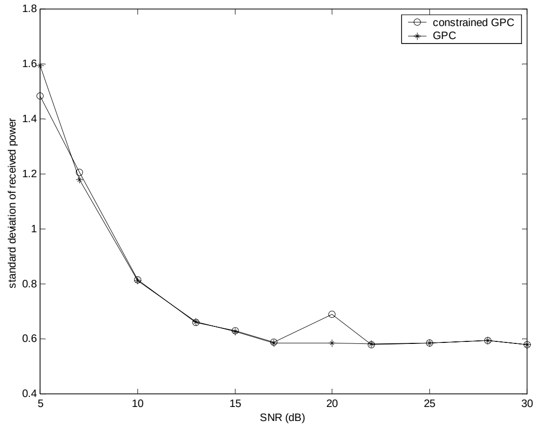

Fig. 3. Standard deviation of the received power as a function of SNR.

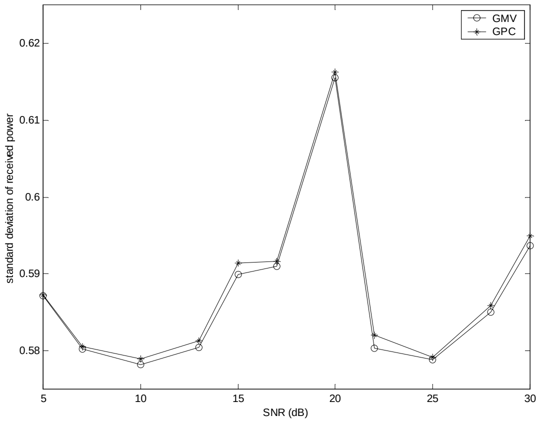

Fig. 4. Standard deviation of the received power as a function of SNR.