Model Predictive Zooming Power Control in Future Cellular Systems Under Coarse Quantization

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***Abstract*—Control signal encoding results in coarse quantization impairments in today's cellular power control loops. The paper proposes a new approach for future cellular systems that enhances performance whilest retaining coarse quantization of the power control signal. The design applies novel optimal model predictive control (MPC) techniques in the base station, based on a model of an adaptive quantization zooming controller in the UE. This allows a high bandwidth with respect to set point changes and disturbances, at the same time as the quantization noise in stationary situations is minimized.**

***Index Terms*—MPC, Cellular Power Control, Adaptive Quantizers**

I. Introduction

Mobile communications play an important role in our society. Today, new applications are entering the market rapidly, driven by the fast growth of systems like the Wideband Code Division Multiple Access (WCDMA) cellular system and the Long Term Evolution (LTE) system [1]. These applications together with new smart phone devices increase the traffic in the cellular networks which need to be met by corresponding performance enhancements. This development is expected to accelerate, putting even harder performance requirements on future technologies.

Technically, due to the very large dynamic range of the received signals, closed loop control of the transmit powers of the user equipments (UEs) is a necessity in the uplink of most cellular systems. Power control in classical CDMA systems is particularly challenging [1], which is the reason why the present paper uses Wideband Code Division Multiple Access (WCDMA) uplink inner power control loop as a case study in the development of new power control schemes. WCDMA inner loop power control regulates the Signal-to-Interference-Ratio (SIR) at the Base Station (BS) for each user in the cell b y regulating the UE transmit power.

As stated above, the dynamic range of uplink power control can be of the order of tens of dB. In this context, the standard bit quantization of $\pm$1dB used for power control e.g. in WCDMA is a major restriction. The slew rate restriction is e.g. a limiting factor during TD-operation in WCDMA, and when the UE encounters deep fading dips. Further, for UE speeds above 30–50 kmph the 1.5 kHz bandwidth of the WCDMA power control loop becomes insufficient, in such cases controller gains should rather be reduced. However, the $\pm$1dB variation counteracts this and creates an idling oscillation. Recent results, yet to be published, also show that delay compensated power control may induce worse limit cycles with larger amplitudes, which is a further reason for this research. As a result, there has been substantial interest in different mechanisms to compensate for the $\pm$1dB impairment [4], [5]. For example, in [2] a modified fixed step power control algorithm was proposed. In [3], a nonlinear scheme for adapting the power was proposed together with channel estimation. In [6]–[8], the authors propose adaptive schemes for adjusting the step size to address quantization and saturation effects. The issue of time delay compensation has been addressed in [9], [10]. Several authors, e.g., in [11], [12], have studied adaptive minimum variance controllers aimed at addressing the issue of time-varying channel and interference models. In [13] a three degree of freedom controller was suggested. In all of this literature the principal focus has been on the encoders and decoders of the control signal.

The contribution of this paper exploits an alternative paradigm for future cellular power control algorithms. A nonlinear decoder is chosen in the UE, followed by a redesign of the controller in the base station, to take account for the modified decoder. The decoder considered here is dynamic and uses a scaling technique to deal with the trade-off between dynamic range and idling errors resulting from the $\pm$1dB bit limitation. Our key contribution is to utilize a special form of Model Predictive Control (MPC) [15] in the base station to best capitalize on the scaling decoder.

The remainder of this paper is organized as follows. Section II introduces notation. Section III describes existing technology, while section IV gives a brief introduction to nonlinear MPC. In section V the contribution of the paper is developed in detail. Section VI describes an explicit form of the control law, while Section VII describes important properties of the obtained feedback control law. Section VIII illustrates performance of the approach via several simulation examples. Section IX finally presents the conclusions.

II. Preliminary Notation and Acronyms

A bold character $\mathbf{x} \in \mathbb{R}^n$ will denote an n-dimensional vector, each element of this vector $x^{(i)}$ corresponds to the i-th element of the vector $\mathbf{x}$. The sampling time in the inner loop power control is taken to be $\Delta = 0.667$ ms, k is used as the time index, $\mathbf{x}_k$ denotes the state at time $k\Delta$. The shift operator q, see [15], [16], will be used when modeling the system.

III. WCDMA Inner Loop Power Control

Inner loop power control lies at the core of the WCDMA system. The standard model considered for the UE is an integrator plus delay. Signals are expressed in the logarithmic domain so that gain and interference ratios appear in an additive fashion. The various components in the inner loop power control are illustrated in Figure 1.

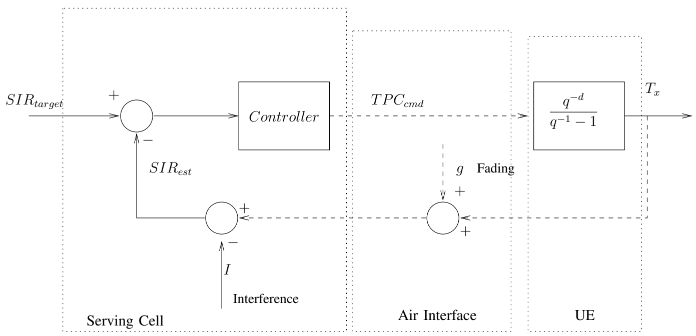

Fig. 1. Standard Inner Power Control Loop

In Figure 1, g denotes the fading factor, while I denotes interference. Interference arises from three different sources: neighboring cells, all other users within the same cell and self-interference, where self-interference represents energy missed e.g. due to misplaced receiver fingers.

The controller, located at the BS in the serving cell, estimates the SIR of the received uplink Dedicated Physical Control CHannel (DPCCH) and generates TPC commands (TPC_{cmd}). In standard implementations, the controller at the BS, issues commands according to the following rule: if $SIR_{est} > SIR_{target}$ then the TPC command transmitted is "0" (-1 dB power step), while if $SIR_{est} < SIR_{target}$ then the TPC command is "1" ($+1$ dB power step). A simple state space model for the UE part of the inner loop power control system in WCDMA is given by,

$$x_{k+1} = x_k + u_{k-d} \quad (1)$$
$$y_k = x_k \quad (2)$$

where $x_k \in \mathbb{R}^1$ denotes the state of the UE and the signal $y_k \in \mathbb{R}^1$ corresponds to the Transmitted Power ("Tx") of the UE. No error appears in (1) since DPCCH coding is relatively strong. The standard control law can be thought of as issuing power increments u_k of the form

$$u_k = sign(y_k + g_k - I_k), \quad (3)$$

where $y_k + g_k - I_k$ corresponds to SIR_{est}, i.e. the estimated SIR at the BS. Here the "per-chip" SIR target rather than "per-bit", or carrier to interference ratio (C/I), is used for simplicity.

IV. Model Predictive Control

The basic concept in MPC [14], [17] is to use a dynamic model to forecast system behavior over some future time horizon and then to use this prediction in a cost function which measures the relative merit of the predicted behavior for different control commands. This cost function is then optimized to generate a control sequence. The first element of this sequence is then implemented. Next, time is advanced one step and the procedure is repeated. The reader is referred to [14], [17] for details.

V. A New Paradigm for Power Control in Future Cellular Systems

In the proposed power control scheme, the control signal decoder in the UE is determined to be a nonlinear scheme with memory. The controller in the BS is then designed to take optimal account for the known decoder algorithm in the UE. The goal of this paradigm shift is to improve performance by allowing faster transient response and lower steady state errors. For simplicity of exposition, the focus is on a single UE not in soft(er) handover [1]. The multiple UE case is terated later, using simulated results.

A. Nonlinear UE Decoder

The first component of the proposed control scheme is that the decoder in the UE includes a dynamic scaling mechanism. It is assumed that the base station can send only one coarsely quantized power control command per slot, which in WCDMA equals one TPC_{cmd}. In the basic WCDMA ILPC scheme used presently the UE interprets the control sequence as ± 1dB increments. This limits the rate of change of the transmit power. To overcome this constraint it is proposed that the decoder interprets two equal consecutive TPC_{cmd} as m times the previous value. That is, for the sequence $\{1,1,1\}$ the UE will increment its power by $\{1, 1\cdot m, 1\cdot m^2\}$dB respectively. On the other hand, when differing TPC_{cmd} are received, it is proposed that the UE will decrease its previous power step by $1/m$ and reverse the sign. That is, the sequence $\{1,0,1\}$ will cause the UE to use the power steps $\{1, -1/m, +1/m^2\}$dB.

As explained in the introduction, similar decoding schemes have been proposed by other authors. The novel contribution of this paper is to change the control law in the base station to make best use of the above zooming quantizer. First note that the delay in (1) is unimportant in the optimization since it only represents an off-set in the control sequence [17]. Also assume that future values of the interference and gain remain constant. Under these conditions, the state equation for the new state model of the UE can be expressed as:

$$x^{(1)}_{k+1} = x^{(1)}_k + x^{(2)}_k, \quad (4)$$
$$x^{(2)}_{k+1} = b_k x^{(2)}_k, \quad (5)$$
$$x^{(3)}_{k+1} = u_k, \quad (6)$$
$$b_k = x^{(3)}_k u_k \frac{m^2+1}{2m} + \frac{m^2-1}{2m},$$

where the computation of b_k is equivalent to:

$$b_k = \begin{cases} m & \text{if } u_k = x^{(3)}_k, \\ -1/m & \text{if } u_k \neq x^{(3)}_k, \end{cases}$$

and where $x^{(1)}_k$ is the current transmitted power by the UE, $x^{(2)}_k$ denotes the power increment at time k and $x^{(3)}_k$ is the previous received TPC_{cmd}. The factor b_k takes the values $-1/m$ or m at each sample depending upon the current and previous control command.

B. Cost Function

The cost function used in the MPC design of the paper is:

$$V(\mathbf{x}_k) = \sum_{i=0}^{N-1} \{(x_{k+i}^{(1)})^2 + (x_{k+i}^{(2)})^2 + (x_{k+i}^{(3)})^2\} + P(x_{k+N}^{(1)})^2 \quad (7)$$

subject to $u_k \in \{-1, 1\}$,
where N is the control horizon.

VI. An explicit Feedback Control Law

In the examples presented in the section VIII, it will be seen that it suffices to use horizon 1 in the optimization problem. In the sequel $P = m$, horizon $N = 1$ are therfore used. One can then transform the output of the optimization problem into a simple static feedback control law, thus eliminating the need to carry out the optimization on-line. This simplifies the implementation and also gives insight into the control law. The key result is :

Lemma 1: The online optimization problem (7) is equivalent to the feedback control law given by:

$$u_k = \begin{cases} u_{k-1}; & 0 > sign(x_k^{(1)}) \cdot x_k^{(2)} > -c_2|x_k^{(1)}| \\ -u_{k-1}; & elsewhere \end{cases} \quad (8)$$

where the positive constant c_2 is given by

$$c_2 = \frac{2(m^2+1)m^2}{m^5 + 3m^4 + 2m^2 - m - 1} \quad (9)$$

Proof: See Appendix A.

VII. Properties of the Control Law

An important property of the scheme is :

Theorem 1: For constant interference and constant channel gain, the trajectories of the state are bounded.

Proof: See Appendix

□□□

The above result admittedly treats an idealized case. For example, in the above result, the power increments are allowed to decrease to zero. In practice it is desirable to introduce a limit on the zooming capability of the algorithm. The reason is that, although it seems desirable to reduce the power increments arbitrarily for a fixed set point and disturbances, this is undesirable if the disturbances and set point change since in the latter case it will take time to build the power increments back up. Hence there is a practical trade-off between the steady state oscillation produced by the minimum allowable power increment and the time needed to build the power increments back up. In the simulations presented below the minimum power increment is chosen to be $|1/m|$.

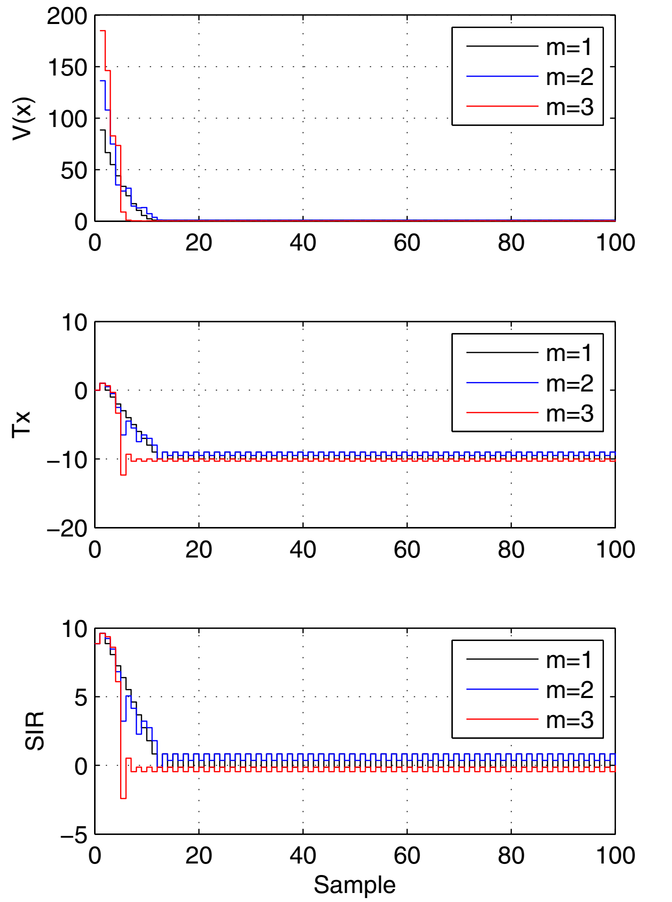

Fig. 2. State regulation: upper plot: Cost function $V(x)$. middle plot: State evolution $x_k^{(1)}$: Tx. lower plot: SIR

VIII. Examples

A. Nominal Case: Horizon 1, single UE

Figure 2 shows the performance of the MPC controller with horizon 1 and three different zooming factors $m = \{1, 2, 3\}$. The channel gain and interference are taken to be constant and a RAKE receiver assumption was used.

The factor $m = 1$ is equivalent to the case when the traditional controller plus a delay compensation mechanism is utilized [18]. To compensate for a change of 10 dB this configuration will require at least 10 slots with this control law. Moreover, in steady state, there will be an oscillation of magnitude $\pm$1dB around the target value. When the factor m is increased a significant improvement in performance occurs. For $m = 2$ the transient time is similar to $m = 1$ (i.e. about 10 slots) but the steady state oscillation is half that achieved with $m = 1$. The factor $m = 3$ reduces the transient time to 4-5 slots, which is less than half the transient with $m = 1$. Also the oscillation in steady state has an amplitude $1/3$ of that seen with a zooming factor of 1. Also, it is worth noticing

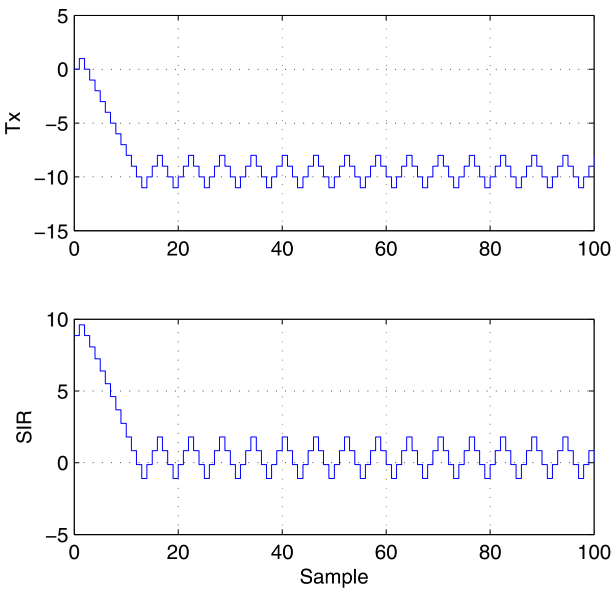

Fig. 3. Tx power and SIR of the current scheme.

that because of the choice of P the cost function of the MPC algorithm decreases in all cases. The algorithm was also tested with horizon 10. Almost identical performance was observed as with horizon $m = 1$. As a comparison, the performance of the existing schemes with the addition of delay compensation [18] is illustrated in Figure 2 since it corresponds to the choice $m = 1$. The case without delay compensation is shown in Figure 3. It can be seen that the UE in the previous scheme experiences longer transient time and increased steady state oscillations, as compared to the UE in the control scheme proposed in this paper.

B. Two UEs with Fading

Here the performance of the different systems are compared when two users are interacting within the same serving cell. A Typical Urban, 3kmph (TU3) fading model was used in a rural setting. This model is highly dispersive.

Figure 4 compares the performance of the previous and the new control schemes. In this case, it is clear that the performance is dramatically improved by using the new MPC based zooming strategy. Oscillations in the systems are drastically decreased. The transmitted power transient of the UEs with the new scheme are significantly less than for the UEs applying the old control scheme.

IX. Conclusions

This paper has described a novel power control scheme for future cellular systems. A first idea is to use an adaptive step size scheme. Similar decoder schemes have been proposed in earlier literature. However, the key novelty of the scheme described here is that also the control law in the base station is modified so as to best utilize the adaptive step size decoder in the UE. A nonlinear MPC strategy is used for this purpose. The paper also showed how an explicit feedback control law can be computed from the MPC optimization problem when the prediction horizon equals 1. The stability of the scheme was analyzed and it was proved that the states remain bounded. Simulations show that the new scheme offers substantially better performance than the existing strategies. Also, the amount of computation needed is extremely small since a prediction horizon of 1 generally suffices in the optimization.

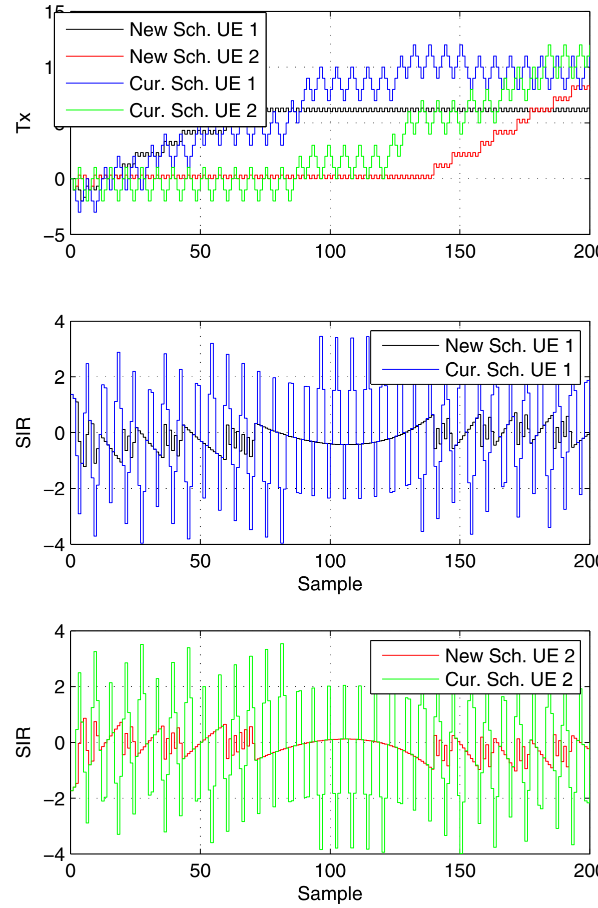

Fig. 4. Upper plot: T_x power. Middle plot: SIR UE 1. Lower plot: SIR UE 2. Rural fading

Appendix A
Proof of Lemma 1

Consider a change of variables defined by $\bar{u} = b_k(u_k))$. Then, $\bar{u}$ can only take values from the set $\bar{u} = \{-1/m; m\}$. Hence the change in the cost function is determined by:

$$\begin{aligned} \Delta V(\mathbf{x}, \bar{u}) &= V(\mathbf{x}_{k+1}) - V(\mathbf{x}_k) \\ &= 2x_k^{(1)} x_k^{(2)}(1 + m\bar{u}) \\ &+ (x_k^{(2)})^2(\bar{u}^2 + 2m\bar{u} + m\bar{u}^2) \end{aligned} \quad (10)$$

Next it is determined by how much the cost function decreases for each control input, i.e. $\bar{u} = -1/m$ ($u_k = -u_{k-1}$) and $\bar{u} = m$ ($u_k = u_{k-1}$). It follows that

$$\Delta V(\mathbf{x}_k, -1/m) = -(x_k^{(2)})^2 \cdot \frac{2}{m^2}(m^2 - 1/2m - 1/2) \quad (11)$$

which is negative for all $m > 1$. Also

$$\Delta V(\mathbf{x}_k, m) = 2x_k^{(1)} x_k^{(2)}(1+m^2) + (x_k^{(2)})^2(3m^2+m^3) \quad (12)$$

which is negative for $x_k^{(2)} < -c_1 x_k^{(1)}$ with $x_k^{(2)} > 0$, and for $x_k^{(2)} > -c_1 x_k^{(1)}$ with $x_k^{(2)} < 0$, where

$$c_1 = \frac{2(1+m^2)}{3m^2+m^3} \quad (13)$$

Now it is known where, and by how much, the cost function decreases in terms of $\mathbf{x}_k$. Hence,

$$\min\{\Delta V(\mathbf{x}_k, -1/m), \Delta V(\mathbf{x}_k, m)\} \quad (14)$$

It is clear that $\Delta V(-1/m) - \Delta V(m) < 0$ when:

$$\begin{aligned} 2x_k^{(1)} x_k^{(2)} m^2(1+m^2) \quad &> \\ -(x_k^{(2)})^2(m^5+3m^4 \quad &+ \quad 2m^2 - m - 1) \end{aligned} \quad (15)$$

Then, defining c_2 as in (9) and noting that $c_2 < c_1$ for all m the result follows.

□□□

Appendix B
Proof of Theorem 1

For $P = m$, $N = 1$, it holds that

$$\begin{aligned} V(\mathbf{x}_k) \quad &= \quad (x_k^{(1)})^2 + (x_k^{(2)})^2 + (x_k^{(3)})^2 \\ &+ \quad P(x_k^{(1)} + x_k^{(2)})^2 \end{aligned} \quad (16)$$

Hence,

$$V(\mathbf{x}_k) \geq \|\mathbf{x}_k\|^2 \quad (17)$$

As in the proof of Lemma 1, define

$$\Delta V(\mathbf{x}_k, \bar{u}) = V(f(\mathbf{x}_k, \bar{u})) - V(\mathbf{x}_k) \quad (18)$$

It has already been established in equation (11) that, with $P = m$, $\Delta V(\mathbf{x}_k, -1/m)$ is negative for all $m > 1$. Moreover, due to the operation of the minimization in the optimization, $\bar{u} = m$ is only chosen when the change in cost is less than when $\bar{u} = -1/m$ is used. Hence, the optimal policy ensures that $\Delta V(\mathbf{x}_k, \bar{u})$ is negative for all time. Therefore $V(\mathbf{x}_k) \leq V(\mathbf{x}_0)$ for all k. Using (17), it follows that

$$\begin{aligned} \|x_k\|^2 \quad &\leq \quad V(\mathbf{x}_k) \quad (19) \\ &\leq \quad V(\mathbf{x}_0) \quad (20) \end{aligned}$$

The result follows.

□□□

Acknowledgment

The research described in this paper was supported by the Australian Research Council Linkage Grant LP0989757 in collaboration with Ericsson AB.

References

[1] E. Dahlman, S. Parkvall, J. Skold, and P. Beming, *3G Evolution*. Academic Press, July 2007. [Online]. Available: http://www.worldcat.org/isbn/012372533X

[2] M. Khan and P. Jain, "A simple modified fixed step size power control algorithm for CDMA cellular systems", in *International Multimedia, Signal Processing and Communication Technologies, IMPACT 09*, 2009, pp. 134–137.

[3] M. Dorpinghaus, L. Schmitt, I. Viering, A. Klein, J. Schmid, G. Ascheid, and H. Meyr, "Enhanced predictive up/down power control for cdma systems," in *IEEE International Conference on Communications, ICC 06*, vol. 9, 2006, pp. 4327–4332.

[4] A. Al Mamun, S. Islam, F. Yesmin, M. Akter, and S. Jahan, "Novel adaptive step power control algorithm for 3g wcdma cellular system," in *12th International Conference on Computers and Information Technology, ICCIT 09*, 2009, pp. 526–530.

[5] C.-C. Lee and R. Steele, "Closed-loop power control in cdma systems," *IEE Proceedings-Communications*, vol. 143, no. 4, pp. 231–239, Aug. 1996.

[6] H. Lee and D.-H. Cho, "A new adaptive power control scheme based on mobile velocity in wireless mobile communication systems," in *IEEE VTS 53rd Vehicular Technology Conference, VTC 2001 Spring*, vol. 4, 2001, pp. 2878–2882.

[7] R. Patachaianand and K. Sandrasegaran, "Performance study of new adaptive power control algorithm," in *International Symposium on Communications and Information Technologies, ISCIT 07*, oct. 2007, pp. 505–510.

[8] R. Patachaianand and K. Sandrasegaran, "Performance comparison of adaptive power control in umts." in *AusWireless 2007. The 2nd International Conference on Wireless Broadband and Ultra Wideband Communications*, aug. 2007, p. 81.

[9] R. Patachaianand and K. Sandrasegaran, "Partial time delay compensation technique for UMTS adaptive power control," *Electronics Letters*, vol. 44, no. 7, pp. 487–488, 2008.

[10] F. Gunnarsson, F. Gustafsson, and J. Blom, "Dynamical effects of time delays and time delay compensation in power controlled ds–cdma," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 1, pp. 141–151, jan 2001.

[11] M. Rintamaki, H. Koivo, and I. Hartimo, "Adaptive closed-loop power control algorithms for CDMA cellular communication systems," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 6, pp. 1756–1768, nov. 2004.

[12] B.-S. Chen, B.-K. Lee, and S.-K. Chen, "Adaptive power control of cellular cdma systems via the optimal predictive model," *IEEE Transactions on Wireless Communications*, vol. 4, no. 4, pp. 1914–1927, july 2005.

[13] J. Aguero, G. Goodwin, K. Lau, M. Wang, E. Silva, and T. Wigren, "Three-degree of freedom adaptive power control for cdma cellular systems," in *IEEE Global Telecommunications Conference, GLOBECOM 2009*, dec. 2009, pp. 1–6.

[14] D. Q. Mayne and J. B. Rawlings, *Model Predictive Control: Theory and Design.* Nob Hill Publishing, 2009.

[15] G. C. Goodwin, S. Graebe, and M. E. Salgado, *Control System Design.* New Jersey, 2001.

[16] A. Feuer and G. Goodwin, *Sampling in Digital Signal Processing and Control.* Cambridge, Mass.: Birkhausser Boston, 1996.

[17] G. C. Goodwin, M. M. Seron, and J. De Dona, *Constrained Control and Estimation, an Optimisational approach.* Springer-Verlag, 2004.

[18] F. Gunnarsson and F. Gustafsson, "Time delay compensation for cdma power control" in *IEEE Global Telecommunications Conference, GLOBECOM 00*, 2000