A Concept of Power Control in Cellular Radio Systems

Fredrik Gunnarsson, Jonas Blom and Fredrik Gustafsson

Department of Electrical Engineering
Linköpings universitet, SE-581 83 Linköping, Sweden
WWW: http://www.control.isy.liu.se
Email: fred@isy.liu.se, jb@isy.liu.se,
fredrik@isy.liu.se

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REGLERTEKNIK

AUTOMATIC CONTROL

LINKÖPING

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Abstract

Due to the rapid expansion of the cellular radio systems market, and the need for wireless multimedia services, the available resources have to be utilized efficiently. A common strategy is to control the transmitter powers of the mobiles and base stations. However, when applying power control to real systems, a number of challenges are prevalent. The performance is limited by time delays, nonlinearities and the availability of measurements and adequate quality measures. In this paper we present a Power Regulator concept, which comprises an Unknown Input Observer, a Quality Mapper and a Power Control Algorithm. The applicability of the concept is exemplified using frequency hopping GSM, and simulations indicate benefits of employing the proposed concept.

Keywords: Cellular radio systems, Power control, Estimation, Nonlinear filters, Delay analysis, PI controllers

1 Introduction

The objective of cellular radio systems is to provide wireless communication in a certain area. This *service area* is divided into a number of cells, which each is served by a *base station*. When a subscriber wants to place a call, he is assigned to a base station (usually the closest one), a radio channel, and a power level to use when transmitting. These assignments are then reconsidered on a regular basis in order to preserve an acceptable connection.

Due to the rapid expansion of the wireless mobile market, and the need for wideband multimedia services, the available bandwidth has to be better utilized. A common strategy in FDMA/TDMA-systems is to reuse the radio channel in the networks according to a reuse pattern. Then a particular channel is used by several base stations in the network, which means that the connections will disturb each other. Therefore it is undesirable to let adjacent base stations use the same channels. In Figure 1, the focus is on the situation on a specific channel used for downlink communication (i.e. base station to mobile station). All transmitted signals are attenuated before they reach the receivers. Assume

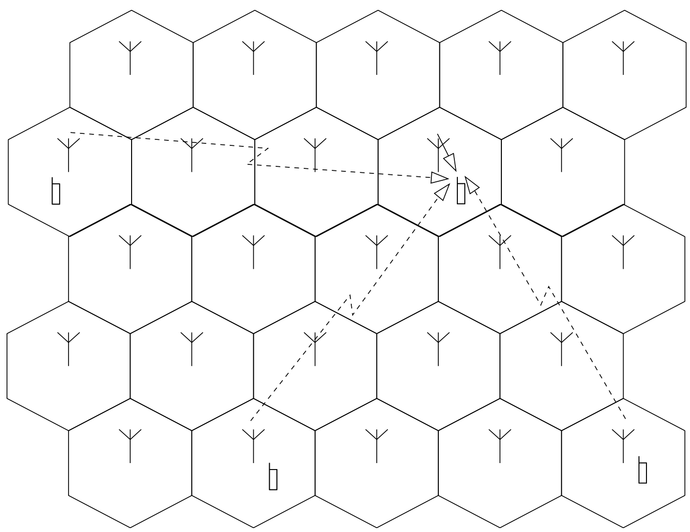

Figure 1: The situation on a specific radio channel in the cellular network, focusing on the signals received at a particular mobile station.. The same channel is used by four different base stations and therefore the connections are disturbing each other.

that base station j is transmitting using the power p_j (in dB). The corresponding power reaching mobile station i is given by $g_{ij} + p_j$, where g_{ij} is the *power gain* capturing the stochastic behavior of the radio channel. Number the mobile and base stations so that mobile station i is connected to base station i. Then mobile station i is observing a desired signal (carrier signal) power C_i, and interference power I_i, which consists of signal powers from other base stations using the same channel and thermal noise ν_i. An important quantity related to the transmission quality is the *carrier-to-interference* ratio, C/I, determined by the ratio of the desired and the undesired signal powers at the receiver. The

C/I at mobile station i is denoted by γ_i.

A user with very good quality may consider to use a lower power and still have acceptable quality. The advantage is that he will disturb other users less, and thereby their quality is improved. Power control is essentially to do the same thing but in a controlled manner.

This is an area of extensive research. Some major contributions can be found in [18, 19, 6, 7, 2, 16, 8, 17, 3].

2 Problem Description

Assume that the appropriate base stations are assigned and channels allocated or at least that they are managed by separate algorithms. Then the remaining problem is to update the output powers of the transmitters. In this section a discussion regarding aspects of power control is provided together with problem formulations. As a matter of fact, the problem can be viewed as either a SISO problem or a decoupled MIMO problem.

The power control problem can be concerned with the following "standard" block diagram if the signals are interpreted as below (with respect to mobile

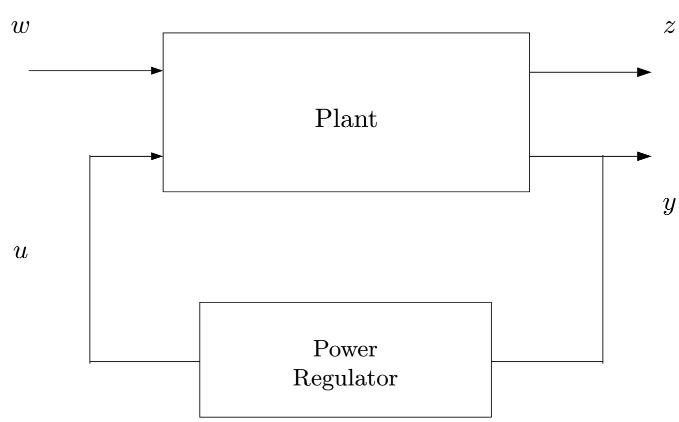

Figure 2: The power control problem formulation.

station i)

- The external disturbances w comprise the power gain g_{ii} and the interference I_i (including the thermal noise ν_i).
- The control signal u is the power level p_i.
- The measurements available to the controller are represented by y. Normally they consist of a quality related and/or a received signal strength related measure.
- Finally z represents an adequate quality measure.

The objective is to assign power levels so that z meets the quality specifications given by z_{ref}. Additionally, it is desirable to provide sufficient quality to as many users as possible, in order to maximize the capacity of the network

We have to formalize the knowledge about the plant. It includes time delays of control signal (n_p samples) and measurements (n_m samples), nonlinearities (given by static function $f(\cdot)$) and how the signals and disturbances relate to the perceived quality and the measurements. The latter are described by the models H, h_1, and h_2. A general description is given in Figure 3, and the incorporated models will be further explored in Section 3.

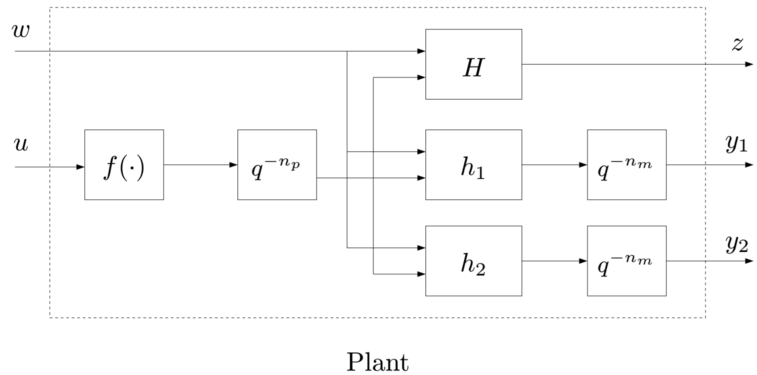

Figure 3: Refinement of the plant. The output power constraints are described by the static nonlinearity $f(\cdot)$, and the time delays by q^{-n_p} and q^{-n_m}. The nonlinear models H, h_1, and h_2 relates the signal power and disturbances to the quality measure and the measurements.

In most literature, it is assumed that the perceived quality is described by the C/I, which is assumed to be measured or observed accurately. Furthermore model the interference at a receiver as an independent disturbance, resulting in a local loop. Valuable information may be obtained through analysis of this simplified control situation, which we will refer to as *SISO control*.

However, since the interference consists of signal powers from other sources controlled analogously, the interconnections affect the performance. When analyzing the interconnected system, we have to consider every assigned output power and every measurement. However, the distributed controllers are still only relying on local measurements. Therefore this case is referred to as *decoupled MIMO control*.

3 Modeling

3.1 Propagation

In order to model the power gain g, the propagation effects can be separated in three terms

$$g = g_p + g_s + g_m.$$

On a long time average, the observed power at the receiver depends mainly on the distance to the transmitter, described by the distance dependent attenuation, g_p.

Terrain variations will result in diffraction and shielding phenomenons, which manifest themselves as a slow variation in this average gain over a distance corresponding to several tens of wavelengths. This effect is referred to as *shadow fading* and is described by the term g_s.

In the presence of several large objects, there will be a great number of reflected signals that reach the receiver. Depending on their phase they interfere either constructively or destructively resulting in *multipath fading* as described by g_m.

For details on modeling these termshow these factors are modeled, see [15, 1, 5]

3.2 Interference

The interference can be modeled as a stochastic variable depending on a number of parameters

$$I = I(m_I, \sigma_1, \ldots, \sigma_n),$$

where m_I is the mean of the interference

As an example, consider frequency hopping GSM, where the characteristics of the interference distribution are approximated by using a simulation model. The gains of the transmitted powers in the random frequency hopping network were modeled by the path loss, shadow fading and multipath fading, as discussed in Section 3.1. Thermal noise was also included in the model. The results are found in Figure 4, from which we conclude that the interference experienced by a user in the network is approximately normal distributed. This result proved to be relatively independent not only of network specific parameters such as cell radius and reuse, but also of the distribution of the transmitted powers. The conclusion is that the interference distribution is characterized by its mean value m_I and its standard deviation σ_I (different for each user). This is a result in the same direction as in [13].

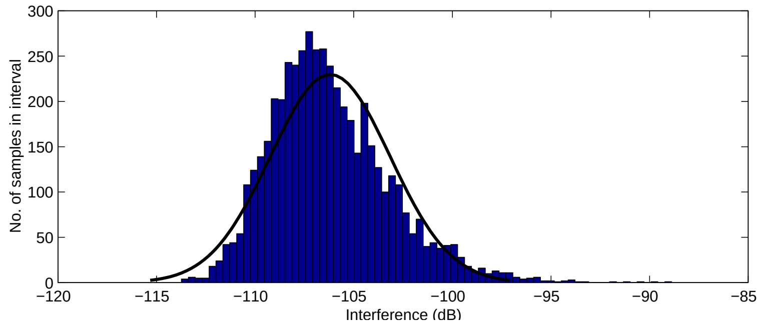

Figure 4: Interference distribution in a random frequency hopping network.

3.3 Measurements

As argued in Section 3.2 the interference is characterized by its mean, m_I, and standard deviation, σ_I. These will affect the outcome of the measurements together with the carrier power, $C_i = p_i + g_{ii}$. The measurements can be modeled as probability functions depending on these parameters.

$$h_i = h_i(C, m_I, \sigma_I), \quad i = 1, 2.$$

In GSM the measurement reports consist of RXLEV and RXQUAL [14]. RXLEV is a signal strength measure, which has been quantized in 64 levels, and RXQUAL is a logarithmic measure of the Bit Error Rate (BER), quantized in 8 levels. In general it is not possible to get simple analytical expressions for these functions. However, *point-mass approximations* can be obtained from simulations for each point in a grid covering the interesting parameter space. Given a point (i.e. a set of parameter values), C- and I-sequences can be generated, from which the measurement report can be formed using models of the modulation. Monte-Carlo simulations yield point-mass approximations of the probability functions as exemplified in Figure 5. The corresponding procedure can be applied when forming the probability function of RXLEV.

3.4 Quality

Similar to the discussion in Section 3.3, the quality function is modeled as a probability function, H, depending on the carrier signal and the interference characteristics. It is relevant to parameterize this function using $\gamma = C - m_I$.

$$H = H(\gamma, \sigma_1, \dots, \sigma_n)$$

Return to the frequency hopping GSM example. Define a *frame* as the bits over which the coding is applied, and assume that a frame will either be fully restored or completely useless. Then the Frame Erasure Rate (FER) can be defined as the percentage of useless frames. This has been argued to describe speech quality well, [12].

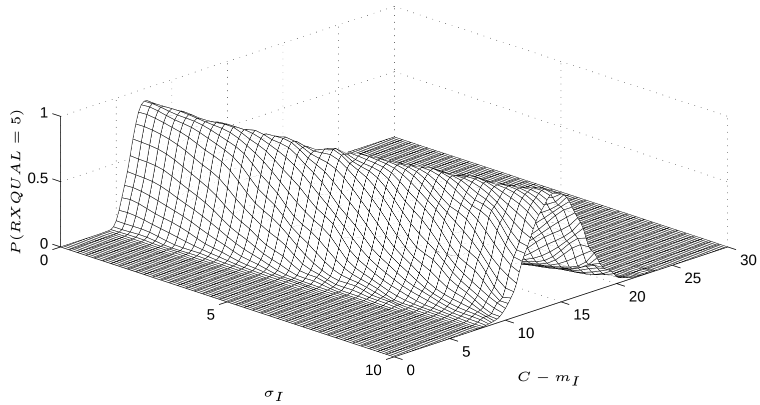

Figure 5: The probability that RXQUAL = 5 is measured for different values of C, m_I and σ_I.

The procedure described in Section 3.3 can be used to form a point-mass approximation of the probability function of FER in a similar manner. The result is provided in Figure 6.

4 The Power Regulator Concept

In this section a solution to the problem formulated in Section 2 is posed. The *Power Regulator* concept to be presented is based on the modeling in the previous section. The solution consists of three parts:

- An *Unknown Input Observer* to extract relevant information from the measurements.
- A *Quality Mapper* (QM) that maps the quality specification onto a C/I reference value, which is more suitable for control.
- A *Power Control Algorithm* (PCA) that determine the appropriate output power.

These components are interconnected as depicted in Figure 7. Basically, the concept is *cascade control* based on quantities from a nonlinear observer. Appropriate design guidelines regarding these three components are provided in the rest of this section.

4.1 Unknown Input Observer

An unknown input observer is designed to extract information about the carrier and interference characteristics from the measurements. There are several possible solutions to this problem, but the proposed solution is based on maximum-likelihood estimation,[11].

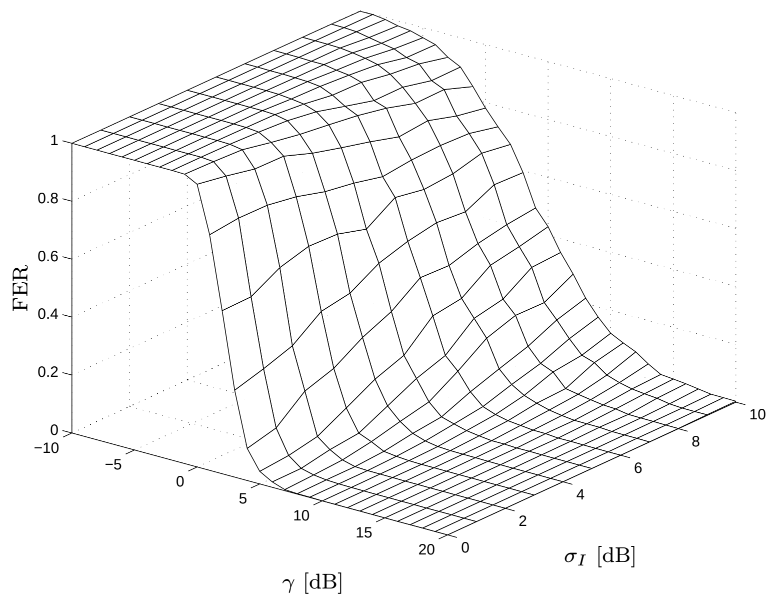

Figure 6: The probability function of FER parameterized using $\gamma = C - m_I$ and σ_I.

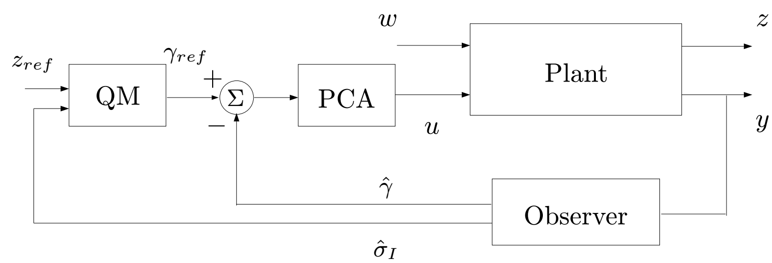

Figure 7: The Power Regulator concept.

Recall from Section 3.3 that in the GSM case the probability functions of the measurements, h_1 and h_2 can be parameterized using $\boldsymbol{\theta} = (C, m_I, \sigma_I)^T$. Let $y_i(t)$ denote the measurement i at time t. In order to track time varying parameters, adaptivity is introduced by employing exponential forgetting of the joint likelihood function

$$\begin{aligned}\log l_t(\boldsymbol{\theta}) =&(1-\lambda)\log h_1(y_1(t),\boldsymbol{\theta})h_2(y_2(t),\boldsymbol{\theta})\\ &+\lambda \log l_{t-1}(\boldsymbol{\theta}).\end{aligned}$$

If the probability function is zero at some grid points for a certain measurement, the value of the likelihood function will remain zero at those points. Consequently, the likelihood function is blocked from growing at those points, inhibiting the adaptivity to varying parameters. A solution is to use a threshold value, h_{min_i}, and when updating the likelihood use the probability function

$$h_i(y,\boldsymbol{\theta}) := \max\{h_i(y,\boldsymbol{\theta}), h_{min_i}\}.$$

The estimate is obtained as

$$\hat{\boldsymbol{\theta}}^{ML}(t) = \arg\max_{\boldsymbol{\theta}} l_t(\boldsymbol{\theta}).$$

Finally, the parameters may be changing at different rates. This is solved by filtering the estimates with different forgetting factors μ_k

$$\hat{\theta}_k(t+1) = (1-\mu_k)\hat{\theta}_k^{ML}(t+1) + \mu_k \hat{\theta}_k(t).$$

4.2 Quality Mapper

One of the objectives of the power regulator is to meet a specified quality level, z_{ref}. The requirement is met if

$$H(\gamma, \sigma_1, \ldots, \sigma_n) \leq z_{ref}.$$

It has been assumed (without loss of generality) that a lower value of z corresponds to better quality.

If H is invertible and monotonically decreasing in γ, this can be solved by

$$\gamma_{ref} \geq H^{-1}(\hat{\sigma}_1, \ldots, \hat{\sigma}_n, z_{ref}),$$

where γ_{ref} corresponds to acceptable quality in terms of z, and is therefore used as the reference value for the inner control loop.

In the frequency hopping GSM example, it is reasonable to specify FER$_{ref}$ = 0.02 = z_{ref}. The corresponding $\gamma_{ref} = H^{-1}(\sigma_I, 0.02)$ is given in Figure 8, and can be implemented in software as a look-up table.

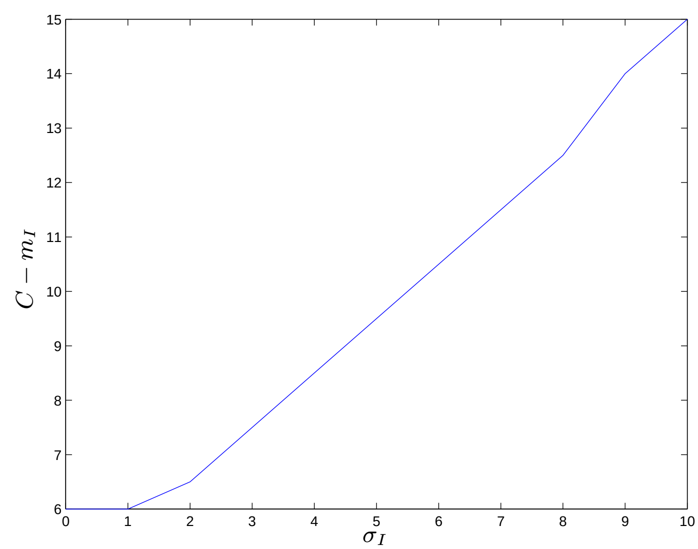

Figure 8: Threshold values for γ, based on the specification FER = 0.02.

4.3 Power Control Algorithm

When applying the power regulator concept as in Figure 7, the objective of the PCA is to track the reference signal obtained from the outer loop. Therefore, a PI-controller may be sufficient.

With this structure, most of previous work regarding power control can be adopted and thereby applied to realistic cases. However, it was shown in [5] that most of the work to date are special cases of or related to

$$p_i(t+1) = p_i(t) + \beta(\gamma_{ref}(t) - \gamma_i(t)), \tag{1}$$

which is a integrating controller. For instance, the Distributed Power Control (DPC) algorithm, [7, 6] algorithm is obtained when $\beta = 1$ and $\gamma_{tgt}(t)$ is constant.

In addition, it may be beneficial to introduce nonlinear components in the controller, such as anti-reset windup, rate limiters, selectors etc. For further details we refer to [4, 5].

5 SISO Control

When the algorithmic properties of the power controller, e.g. convergence and settling time, are to be studied, it may be easier to assume that the interesting values are at hand, and that quality is related to simple measures. For example, it is common to assume that the transmission quality is only dependent on the C/I and that this value is at hand. Furthermore, if the interference is modeled as an independent disturbance, the local control loops can be analyzed individually.

As noted in Section 2, time delays and constraints are always present in real systems, and there is a need for tools to analyze their effects. In this case, the situation in Figures 3 and 7 can be simplified and depicted as in Figure 9. Stability analysis of this inner loop model using root locus and describing functions is provided in [5, 9]

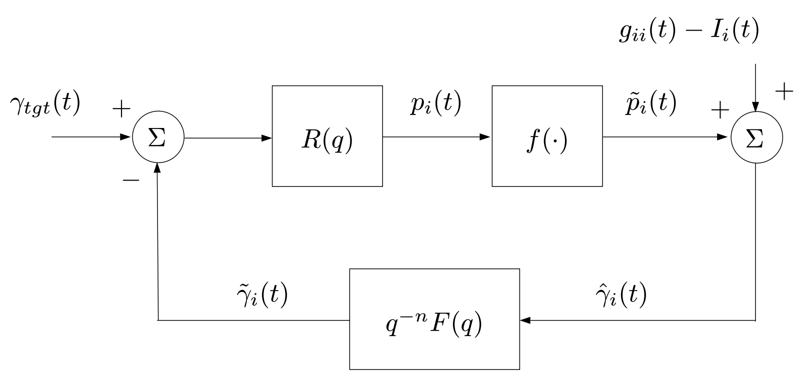

Figure 9: Simplified block diagram of SISO control.

6 Decoupled MIMO Control

It is hard to analyze the performance of the decoupled MIMO control system analytically due to the presence of nonlinearities, constraints and also due to the complexity of the measurements. Therefore simulation environments are appropriate to use for these evaluations. In order to illuminate the stability and convergence properties of the algorithms, we will study a case, where four mobile stations have controlled their powers for a sufficiently long time so that their corresponding powers have converged or at least meet the quality requirements. At time instant $t = 0$, a fifth mobile station establishes a call on the same channel, initially using maximum power.

The performance of the power control algorithm (1) is illustrated in Figure 10, where the total time delay is $n = n_p + n_m = 2$. Note that the celebrated DPC algorithm ($\beta = 1$) gets unstable. As shown in SISO control analysis (discussed in [5, 10, 9]) and further illuminated by these simulations, stability can be preserved by choosing a smaller β.

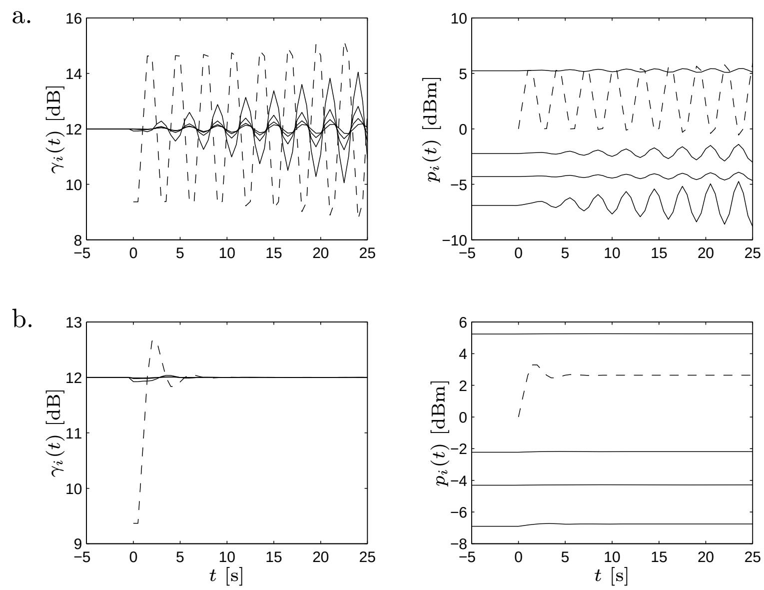

Figure 10: The response to an entering mobile station, when subject to time delays using different parameter values. In the left column, the various C/I values are plotted, while the corresponding power levels are given in the right column. The dashed curves corresponds to the newly established connection. a. I-controller, $\beta = 1$, b. I-controller, $\beta = 0.3$.

To see whether the quality mapper further improves the performance of the system, and if the performance is degraded by imperfect estimates, extensive simulations using a network emulator have been performed. As seen in Figure 11, the percentage of satisfied customers is further increased when employing the quality mapper. Moreover, power savings of about 6 dB on an average are recorded.

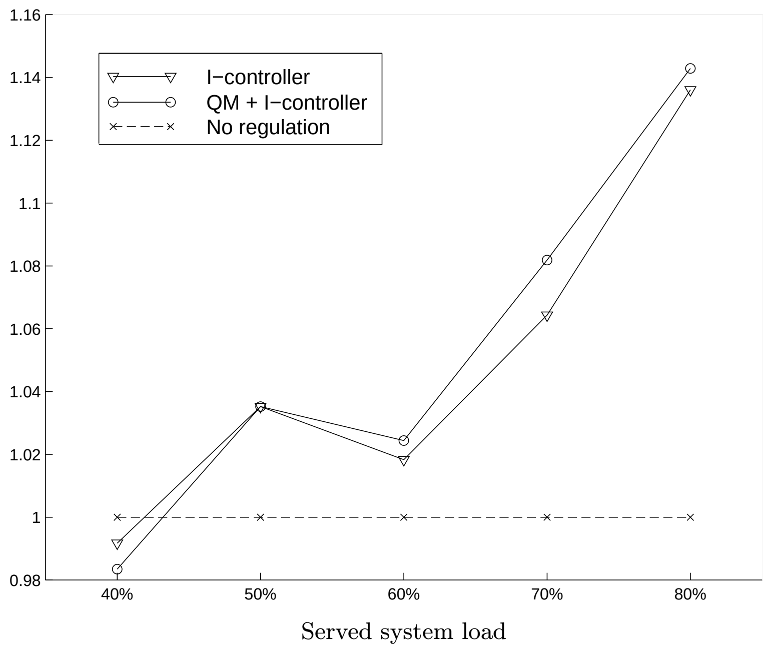

Figure 11: The percentage of satisfied customers for various served system load and algorithms relative to the number of satisfied customers when using constant maximum power.

7 Conclusions

A new concept of power control in cellular systems is proposed. It is based on a Unknown Input Observer, a Quality Mapper and a Power Control Algorithm. From a control perspective it can be seen as a cascade controller, where the the Quality Mapper determines the reference value to the inner loop based on estimates from the observer. The Power Control Algorithm in the inner loop updates the power so that the estimated signal tracks the computed reference signal.

With this structure, the stability of the inner loop can be analyzed separately to provide valuable insight. Such inner loop analysis is referred to as SISO control, and is based on an assumption of the interference as an independent disturbance. However, it is composed by signals from other transmitters, and these interconnections affect the overall performance. Due to the complexity of the measurements and quality measures, these effects are hard to analyze analytically. Instead, simulations have been performed, which indicates the performance gains of using the proposed concept. Capacity gains of up to 15% are observed in these simulations. In addition, power savings of about 6 dB on an average are recorded.

The concept is ready for implementation in a second generation wireless system. The only component of the cellular system that has to be updated is the software in the base stations, where the output powers are computed. Hence it can be applied without affecting the standard, the mobile terminals, the radio interfaces, or the base station transmitters. This is very important, because of the great number of terminals in use in todays systems. However, the concept is general and will be useful in a third generation wireless system as well.

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