A New Concept of Power Control in Cellular Systems Reflecting Challenges of Today's Systems

Jonas Blom, Fredrik Gunnarsson and Fredrik Gustafsson

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

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Abstract

When the systems evolved from analog to digital, the performance was improved by the use of power control on the one hand and different modulations and coding schemes on the other. Condensing the available information we are able to propose a new concept of power control. The concept is applicable to real systems, since it uses the available measurements for estimating parameters necessary for the power control. It also supports the use of an adequate quality measure together with a quality specification supplied by the operator. We will use frequency hopping GSM as an example and the resulting control algorithm is ready for implementation in the software in the base stations where the output powers are computed. No modifications are needed in the GSM standard, the mobile terminals, the radio interfaces or in the base station transmitters. Finally we provide simulation results confirming the benefits of using the new concept for power control.

Keywords: Cellular radio systems; Power Regulators; Power Control Algorithms; ML Estimation; Quality mapping; Frame erasure rate

1 Introduction

Several methods and strategies to control the power in cellular radio systems have been proposed [18, 17, 5, 6, 1, 15, 7, 16, 3]. Based on some simplifying assumptions, corresponding convergence results have been established. In most previous work rather ideal cases are considered. When considering power control in real systems, we find the following aspects interesting.

Quality Measure. Speech quality is a very subjective quantity. People have argued that C/I is an adequate objective measure, and it has been used extensively in previous works, even though it is far from ideal.

Available Measurements. Usually the measurements are given in reports comprising a *Quality Indicator* (QI), reflecting the quality and a *Received Signal Strength Indicator* (RSSI), reflecting the received signal strength at the receiver. These values are coarsely quantized in order to use few bits.

Constraints. The output power levels are limited to a given set of values due to hardware constraints. This includes quantizing and the fact that the output power has an upper and a lower limit.

Time Delays. Measuring and control signaling take time, which results in time delays in the network.

In this paper the focus will be on how to handle quality specifications and the available measurements. We propose a concept for resolving these problems. For a more thorough discussion about the concept, we refer to [4, 8]. The problems with constraints and time delays are the subject of the accompanying paper [9].

The surrounding environment as seen by the power controller, can be described as in Figure 1. Note that the chosen quality measure is not necessarily measurable directly.

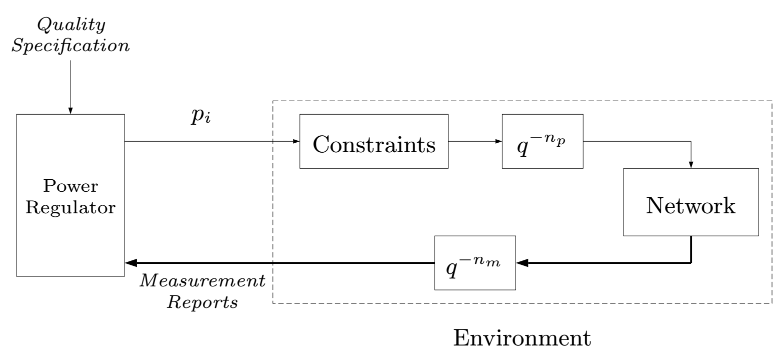

Figure 1: The surrounding *Environment* as seen by a decentralized controller, when considering time delays and constraints. The *Network* block incorporates the effects caused by the radio channel, such as power gain, noise and interfering transmitters. p_i is the output power, while n_p and n_m represent delays.

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. Then we refer to this power controlling component as the *Power Control Algorithm* (PCA). This includes most of the algorithms developed in this area to date. On the other hand when discussing a complete solution that fits into the interfaces of existing systems, we use the term *Power Regulator* (PR).

2 A New Concept of Power Control

The proposed *Power Regulator* is comprising three parts as within the dashed lines in Figure 2. Altogether, given measurement reports, it will update the transmitter power in order to meet the specified quality. All transmitter powers in the network can be controlled by identical regulators. However it is important to note that even though the regulators are identical, they adapt to the individual situations experienced at each receiver, in order to achieve the specified quality.

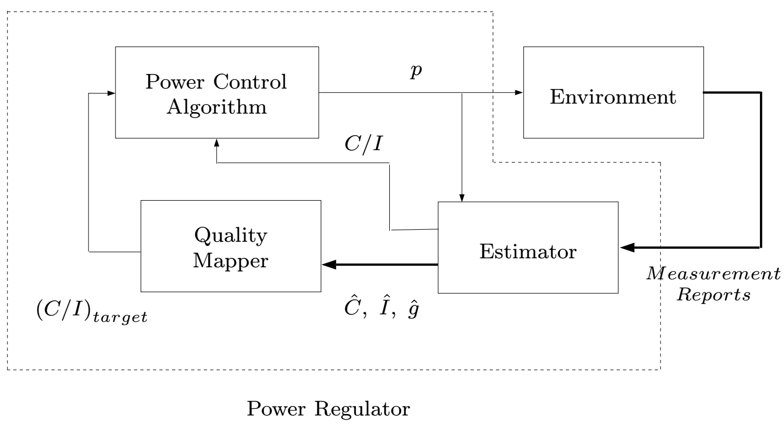

Figure 2: The proposed Power Regulator can be divided into the three parts: Estimator, Quality Mapper and Power Control Algorithm. All transmitter powers in the network are controlled by identical Power Regulators, but each of them is adapting to the individual situation.

2.1 The Estimator

The problem of estimating the C/I was addressed in [2, 14], but that approach assumes that analog signal strength measurements are available. In a real situation, the available information is given in measurement reports and one of the core problems is to extract as much relevant information as possible from these reports. Therefore we introduce an *Estimator* which will estimate the carrier C, the interference distribution I, and compute the path loss $g = C - p$ and the C/I. The information available to the estimator are the RSSI and the QI in the measurement reports, which in turn are depending on the parameters to be estimated. Hence, the measurement reports contain information from two conceptually different information sources. The estimator can be constructed in numerous ways, but we have chosen a Maximum Likelihood (ML) estimator, since it is successfully enables this data fusion and is an implementationally simple algorithm.

The method of ML estimation is based on a simple idea. Different probability density functions generate different data samples and any given data sample is more likely to have come from a particular distribution than from others. We will not go into the basic details of how ML estimation is implemented, instead, we refer the reader who is not familiar with these concepts to [10].

Let x_t denote a measurement at time t, θ the parameters describing the interference distribution together with the carrier. The likelihood of a single measurement, $f_X(x_t;\theta) = f_1(x_t;\theta) \cdot f_2(x_t;\theta)$ is a product of two likelihoods; one for the RSSI and one for the QI.

An adaptive algorithm (one that is able to track a varying parameter) should be used for ML estimation. Since the latest measurements contain more current information, the adaptive algorithm used should rely more on them. In order to accomplish this adaptive use of the latest measurements, a *forgetting factor*, λ, is introduced in the likelihood function $l_t(\theta)$

$$l_t(\theta) = f_X(x_t;\theta) f_X(x_{t-1};\theta)^{\lambda} \cdots f_X(x_1;\theta)^{\lambda^{t-1}} \tag{1}$$

Using $\lambda = 0$ corresponds to “maximal forgetting”, i.e. only the last measurement is considered, and $\lambda = 1$ gives equal weight to all measurements. The following recursive expression can be used to implement the exponential “forgetting”

$$\log l_t(\theta) = \log f_X(x_t;\theta) + \lambda \log l_{t-1}(\theta)$$

The estimate, θ is then obtained as the values which maximize the likelihood function. In order to obtain smooth estimates, it is preferable to filter each of the estimates separately, since they change at different rates. Exponential filtering is suitable for this purpose, see [9].

2.2 The Quality Mapper

There are a wide range of quality measure candidates, ranging from *Bit Error Rate* (BER) and *Frame Erasure Rates* (FER) to measures based on subjective listener tests. Regardless of which of these we choose, it can be desirable for the network operator to be able to specify the quality using a measure that reflects the tradeoff between capacity and speech quality. This is implemented in the *Quality Mapper* which acts as the glue between the estimator and the power control algorithm, by mapping the chosen quality measure onto a target C/I using the estimated parameters.

When the power regulator is in use, the quality mapper calculates appropriate target C/I values from the estimated quantities. From this point of view, the quality mapper is nothing but a look-up table. This table can be constructed from a quality function together with a specification of the required quality prior to the start-up of the system. Assume that the quality measure values can be described by a *quality function*

$$Q(\gamma; \theta_1, \ldots, \theta_n)$$

where γ denotes the C/I and $\theta_1, \ldots, \theta_n$ denote quantities parameterizing the interference distribution. This function, which describes an objective quality measure, may be obtained from a model or from measurements.

If Q_0 denote the limit between acceptable and unacceptable quality, it is required

$$Q(\gamma; \theta_1, \ldots, \theta_n) \leq Q_0$$

in order to get acceptable quality. It has been assumed (without loss of generality) that a lower value of Q corresponds to better quality. If Q is invertible and monotonically decreasing in γ, this can be solved simply by controlling γ to fulfill

$$\gamma \geq Q^{-1}(Q_0; \hat{\theta}_1, \ldots, \hat{\theta}_n),$$

The right-hand side implements the necessary quality mapping. In practice, the estimates are used in the quality mapper, as indicated in the equation above. The case where the quality function is non-invertible is solved in [4].

2.3 The Power Control Algorithm

When the solution is broken down into three parts, the functionality of the *power control algorithm* is to assign the appropriate power level so that the measured C/I will track the target C/I. When an estimated C/I and a target C/I are available, several proposed algorithms are applicable, for instance the Distributed Power Control (DPC) algorithm [5], the algorithm proposed by Almgren, Andersson and Wallstedt (AAW) in [1] and a PID controller [4]. For a more thorough discussion about these algorithms, we refer to [4, 9].

3 Example: Frequency Hopping GSM

Note that the methods discussed this far are general, but in this section we will refine them, and apply them to frequency hopping GSM. As discussed in Section 2, the interference distribution must be parameterized by a number of parameters. In order to find these, we used a simulation model where it is assumed that the interference is constant during a burst. The gains of the transmitted powers in the random frequency hopping network were modeled by the path loss, shadow fading and Rayleigh fading. Thermal noise was also included in the model for the interference. The results are found in Figure 3 from which we conclude that the interference experienced by a user in the network is approximately normal distributed. This approximation is better for higher channel utilizations, which is a term describing the fraction of the available

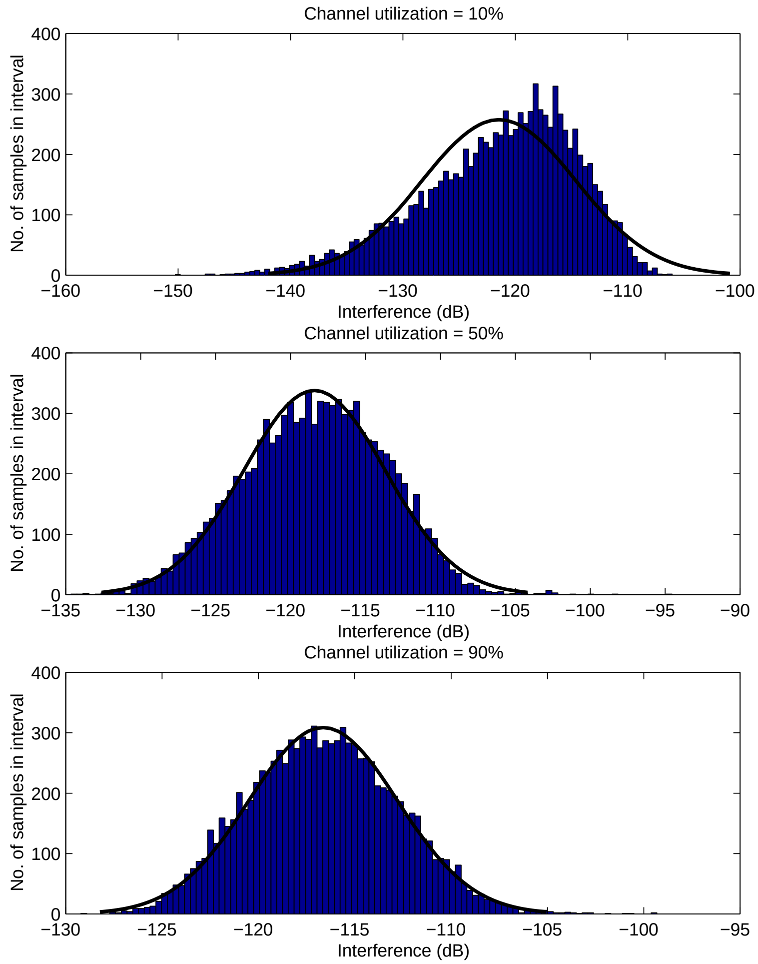

Figure 3: Interference distribution in a random frequency hopping network. The channel utilization (or interference load) refers to the extent to which the channel is used.

communication links which are occupied. 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 from this is that the interference distribution is characterized by its mean value m_I and its standard deviation σ_I. This is supported by theoretical results, see [13, 12]. Our results hold on the burst time scale, i.e. for each burst the interference can be viewed as given by a realization of this normal distribution. Estimators used in previous work are only characterizing the interference by its mean value, see e.g. [1], and therefore this approach describes the interference more thoroughly.

Since the power can only be updated once every 0.48 s, we can not control the power to compensate for the fast multi-path fading, which is relatively constant during a burst, but varies considerably over a frame. Instead, the time and interferer diversity will limit the influence of the fading.

The correlation distance for the shadow fading typically has the value 100 m. For a vehicle traveling at 30 m/s, this distance will take ≈ 3.3 s to travel. This time is relatively long compared to the power update interval, 0.48 s, and thus we expect to be able to compensate for these variations. The same conclusion holds for the path loss, which is slowly varying.

3.1 Choice of Estimator

According to the discussion in Section II.2.1 we want the estimator to estimate carrier power, C, together with the mean, m_I, and the standard deviation, σ_I, of the interference. These estimates will be denoted by $\hat{C}$, $\hat{m}_I$ and $\hat{\sigma}_I$. Together with the transmission power, these estimates can be used for calculating the path loss $\hat{g} = \hat{C} - p$ and the C/I estimate ($\widehat{C/I} = \hat{C} - \hat{m}_I$).

In GSM the measurement reports consist of RXLEV and RXQUAL. RXLEV is a signal strength measure, which has been quantized in 64 levels, and RXQUAL is a logarithmic measure of the bit error probability, quantized in 8 levels. As discussed in Section II.2.1, x denotes the measurements and θ the parameters to be estimated

$$\begin{aligned} x &= (\mathrm{R}XLEV,\ \mathrm{R}XQUAL)^T \\ \theta &= (C, m_I, \sigma_I)^T. \end{aligned}$$

The function $f(x, \theta)$ is found by simulations on the burst time scale using a model of the receiver together with the GSM standard.

Using simulations we can generate measurement reports as in the GSM system. In Figure 4 and 5, we find the results when estimating the carrier and C/I from the measurement reports with the estimator described above. Despite the loss of information in the quantization, the estimates are reasonably accurate.

3.2 Choice of Quality Mapper

It has been argued that FER is an appropriate objective measure of speech quality when considering a TDMA system [11]. Hence, we use this as the quality function, and using a model of the receiver we construct it similarly to [11]. A good estimate of FER can be obtained by repeating this process several times for every point in the grid and forming the average.

The result of the procedure above is shown in Figure 6. This shows how the FER depends on the different estimated parameters.

For the quality mapper algorithm, a specified maximum allowable FER is input by the operator. In this example we choose FER = 2%, see [11]. Using the procedure outlined in Section II.2.2 for this quality specification, we obtain a.

b.

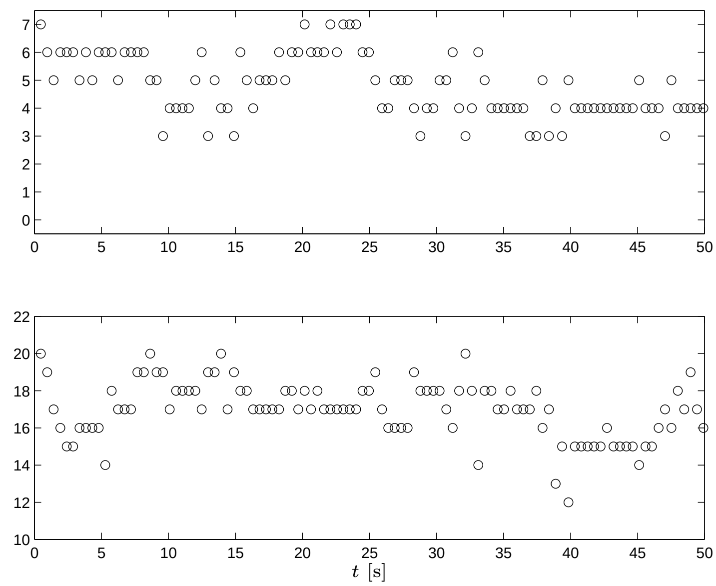

Figure 4: Measurement reports, consisting of a. RXQUAL and b. RXLEV, describing the perceived quality and signal strength respectively. These values are fed to the estimator.

a look-up table, see Figure 7. By controlling the carrier power such that we exceed the threshold in this figure, we can achieve the specified quality.

In a normal traffic situation, a C/I equal to 10 dB corresponds to an acceptable speech quality. For comparison purposes we can study such a normal traffic situation using simulations, from which it is found that the estimated standard deviation of the interference, σ_I, is typically 6 dB, which is also indicated by the Monte Carlo simulations in Figure 3. As demonstrated by Figure 7, this estimated σ_I yields a target C/I of 10 dB in order to achieve FER = 2%, and thus our approach in this typical case covers the traditional opinion that a C/I of 10 dB corresponds to acceptable quality. However, we can conclude that a lower standard deviation will allow C/I to be less than 10 dB without losing quality. Hence a lower power can be used, and this will enable additional gains in capacity. Conversely, for $\sigma_I > 6$ dB our algorithm recognizes the need to increase the C/I above 10 dB in order to maintain acceptable quality.

3.3 Choice of Power Control Algorithm

In the current setting, the choice of power control algorithm is not depending on the type of cellular system. Therefore, we refer to the general case discussed in Section II.2.3

a.

b.

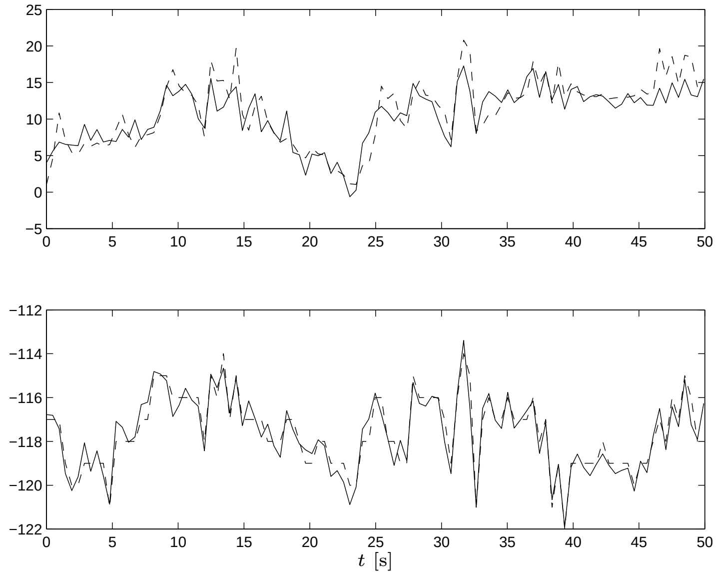

Figure 5: Given the measurement reports in Figure 4 the estimator extracts e.g. a. C/I and b. Carrier. The estimated values are shown by the solid lines, and the true values by dashed.

4 Simulations

In order to test if the concept with quality mapping is beneficial, we performed frequency hopping GSM system simulations. The situations on the different channels are not independent, and leakage between the channel has to be considered. Hence, we have to consider all the channels used in the system. Furthermore, the channel reuse is an important part and has to be taken into account.

The duration of one burst is 0.577 ms in GSM. During this time, the multi-path fading is assumed to be constant. Furthermore assume that no user has a Line-of-Sight connection to the base station. Therefore the multi-path fading can be modeled as Rayleigh fading. The fading is correlated both in frequency and space, which has to be considered when simulating a system based on several carrier frequencies. Control signaling such as measurement reports and power control commands are transmitted more seldom. In total, 104 bursts are simulated each control signaling sample time T_c, resulting in $T_c = 0.48$ s (considering the fact that there are eight time slots). The simulation conditions are summarized in Table 1.

The percentage of satisfied users will be taken as performance measure. We consider a user to be satisfied if the corresponding average FER over time is below 0.02. In Figure 8, the number of satisfied users for different loads and algorithms can be found. These are shown relative to the number of satisfied users when all transmitters use the same constant power. The corresponding mean

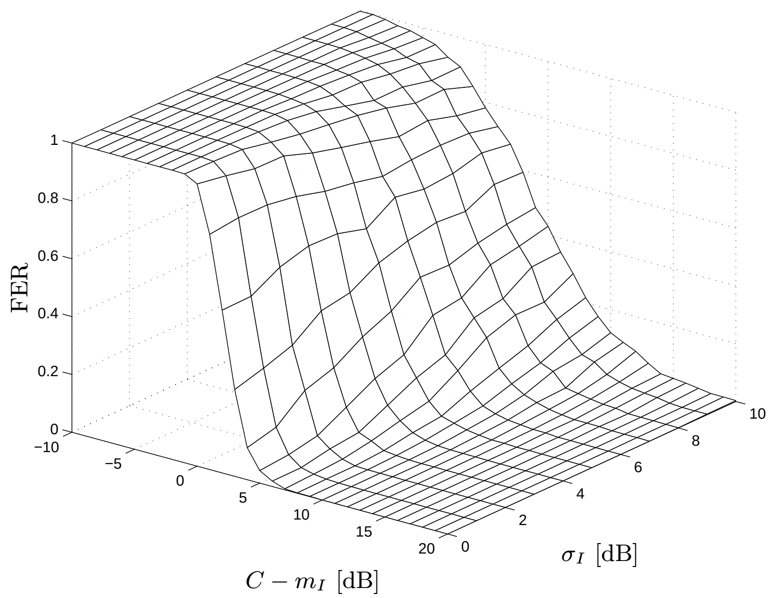

Figure 6: Frame erasure rate as a function of the carrier and the interference parameters for GSM.

powers used in the network are shown in Figure 9. By comparing the results for the I-controller with and without quality mapping, we find that additional capacity can be gained by including the quality mapper in the system.

5 Summary

We have presented a new concept of power control in cellular systems. Our power regulator is built up by three parts: The estimator, the quality mapper and the power control algorithm. We believe that the main features of this concept are that:

- It is ready for implementation in a second generation wireless system. The only component in the cellular system that has to be updated is the software in the base stations, where the output powers are computed. However, the concept is general and will be useful in a third generation wireless system as well.
- The transmission quality requirements can be specified using a measure that better reflects the actual quality perceived by the users. When considering frequency hopping GSM, the Frame Erasure Rate (FER) is an adequate quality measure.
- Using an estimator we are able to extract as much relevant information as possible from the measurement reports, such as the interference characteristics, the path loss, the carrier and the C/I.

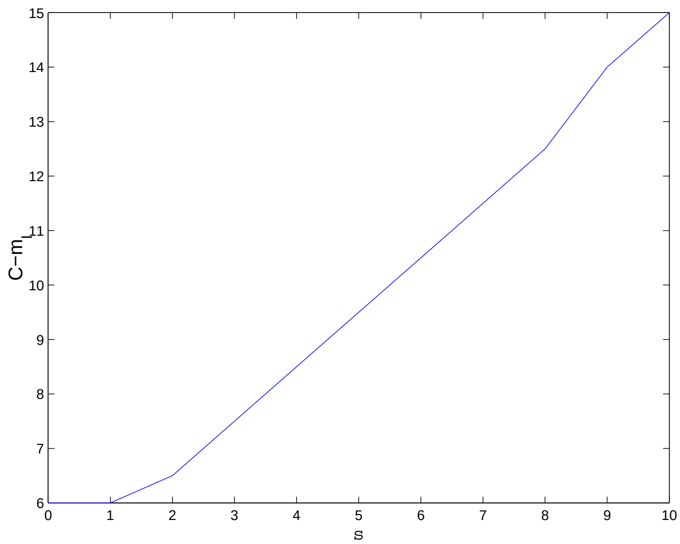

Figure 7: Threshold values for C/I $(C - m_I)$, based on the specification FER = 0.02.

- When using the estimator and the quality mapper as described, the function of the power control algorithm is reduced to assigning transmitter power levels so that the estimated C/I will track the computed target C/I, in order to achieve the specified quality. Several of the power control algorithms suggested in the literature fit into this framework.

From the GSM example we find that using a quality mapper a lower power can be used when the standard deviation of the interference is low. On the contrary, when the standard deviation is high, this will be detected and the power will be increased in order to avoid speech quality degradations. System simulations show that additional capacity can be gained by using a quality mapper.

Frequency band	900 MHz
No. of carrier freq.	27
Frequency reuse	K = 9
Antennas	Sectorized
Cell radius	1000 m
Cell layout	5×5 clusters of 9 cells, employing wrap around
Adj. channel atten.	-20 dB
Frequency hopping	Pseudo-random
Path-loss exponent	$\alpha = 3.5$
Shadow fading std.dev.	$\sigma_s = 6$ dB
Shadow fading corr.dist.	$d = 100$ m
Rayl. fading, avg. gain	0 dB
Control sample interval	$T_c = 0.48$ s
Burst time	0.577 ms
Mean MS speed	50 km/h
Downlink power	13 dBW (constant)
Uplink MS:	GSM class 4:
Uplink maximum power	$p_{max} = 3$ dBW
Uplink minimum power	$p_{min} = -17$ dBW
Uplink quantization	2 dB

Table 1: System simulation parameters.

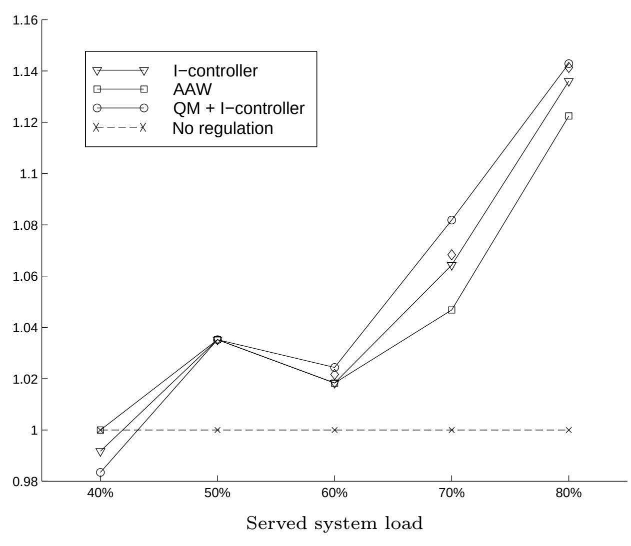

Figure 8: The number of satisfied customers for various served system load and algorithms relative to the number of satisfied customers when using constant maximum power.

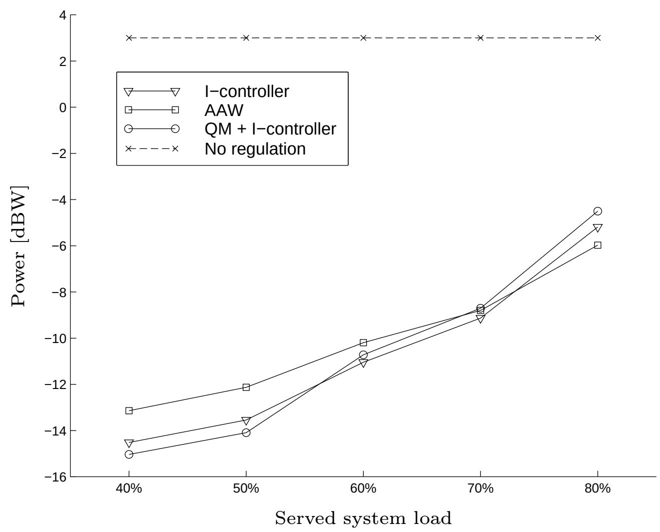

Figure 9: The mean power used in the network for various served system load and algorithms.

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