Estimating the QoS Enhancement Using Power Control in EGPRS*

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Abstract – **Second-generation (2G) systems popularized wireless telephony services. Third-generation (3G) systems are expected to enhance 2G systems with high data rates and multimedia capabilities. In this context, EGPRS, the packet data service of the GSM/EDGE Radio Access Network, becomes even more important, due to its 2G compatibility and its capability to achieve high packet data rates (above 384 Kbps) using 8-PSK modulation and a sophisticated Link Quality Control scheme. In order to satisfy the increasing demand for wireless services and to improve system capacity, many techniques, such as power control, smart antennas, dynamic channel allocation, and traffic scheduling, were proposed in the literature. In this work, we examine two different power control algorithms applied within the EGPRS context. For each algorithm, several simulations were performed, and the obtained results include SINR and throughput distributions, as well as QoS gains in terms of 10th percentile throughput values. Uplink State Flag (USF) reliable reception and its impact on power control performance is also inspected.**

I. Introduction

SECOND-generation (2G) systems around the world were responsible for taking mobile communications to the mass market, mainly through the provision of wide area wireless telephony services. Third-generation (3G) systems are expected to enhance 2G systems with high data rates and multimedia capabilities, which is increasingly becoming equivalent to providing good Internet access. Despite the current low rate or return and delays in network and terminal deployment, market forecasts for 3G systems continue to be very promising. The UMTS Forum, the independent body which promotes the global uptake of 3G mobile systems and services, published in August 2001 a market study estimating the revenue potential of 3G networks. Service revenue is predicted to represent a substantial market opportunity of US$320 billion in 2010 alone, and around US$1 trillion over the decade as a whole [1, 2]. A large fraction of these revenues will be due to new third-generation services, such as high speed web browsing, streaming audio and video, full duplex voice and video over IP, multimedia messaging service (MMS), and enhanced e-mail. Of course, such promising scenario is based on increasing technology penetration and progress.

The GSM/EDGE Radio Access Network (GERAN) is one of the radio access technologies of the Universal Mobile Telecommunications System (UMTS), a leading 3G standard. Among the advantages provided by GERAN are the ability to operate in existing 2G spectrum bands with high efficiency, lower operating costs and increased revenues, and provision of 3G services even in wide coverage areas, such as low density rural areas. GERAN may operate in both circuit- or packet-switched modes.

As the telecommunications world shifts towards packet-switching, the Enhanced General Packet Radio Service (EGPRS) of GERAN becomes even more important. EGPRS is built on top of the Enhanced Data Rates for Global Evolution (EDGE) concept, which uses 8-PSK modulation in addition to GMSK and an efficient Link Quality Control (LQC) mechanism. These features enable EGPRS to achieve data rates above 384 Kbps and spectral efficiency 2.5-6 times higher than standard GPRS for any quality of service (bit rate) requirement. There are two LQC modes in EDGE, namely Link Adaptation (LA) and Incremental Redundancy (IR). IR outperforms LA due to its faster response to variations in the link quality at the cost of increased complexity and implementation costs. LA has been specified as mandatory while IR as optional.

The steadily increasing number of mobile communication subscribers is the main driver for capacity enhancement techniques, such as power control (PC), smart antennas, channel allocation and traffic scheduling. Power control, in particular, is an effective method of reducing co-channel interference, which can be traded for capacity. In the forward link (downlink), users sharing the same channel in different base stations perceive signals from other users as co-channel interference. Therefore, keeping transmission power levels at minimum required values improves signal quality for all users. In the reverse link, power control is also important in helping extending battery lifetime and diminishing the near-far effect (in CDMA systems).

Basically, power control algorithms may be organized in two groups: open-loop and closed-loop. Open-loop algorithms estimate the channel conditions and adjust the transmission power accordingly. There is no feedback regarding the effectiveness of the applied power control, which makes these algorithms less computationally de-

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manding, but also less precise. Closed-loop algorithms normally base their decisions upon link quality measurements and estimates, such as power level, signal-to-interference-plus-noise ratio (SINR), and frame error rate. Moreover, these algorithms may make centralized or decentralized decisions. The former approach requires a more complex signaling and processing infrastructure.

Although power control algorithms have been extensively studied for circuit-switched services, packet-switched services like EGPRS offer new challenges and require specific investigation. EGPRS working in LA mode, for instance, allows the maintenance of a data connection in a wide range of signal quality, adapting the data rate accordingly. Therefore, power control algorithms may no longer be adjusted with the simple assumption of satisfying a unique signal quality threshold, as it was the case for voice services. Furthermore, standard-specific issues, such as in-band signaling and feedback delays, may pose additional problems.

In this work, two downlink power control algorithms are studied in the context of the EGPRS packet data service. Section II introduces the PC algorithms. Section III presents the simulation model and GERAN information related to link quality control performance, power control and other issues. Section IV presents more details about the simulations. In section V, results are presented and discussed. Section VI concludes this work with a brief summary.

II. Power Control Algorithms

We have considered two downlink distributed power control algorithms: autonomous SINR balancing algorithm (SINR PC) and signal-level-based algorithm (Signal-level-based PC). The former aims at balancing the individual SINRs of Q co-channel mobile stations towards the desired SINR ρ, while the latter is based on half-compensation of the path gain at each downlink. Both algorithms are fully distributed, since they make use of local measures.

The determination of the ρ parameter, in the case of the first algorithm, is an important issue, because the SINR balancing effect will only be achieved under certain circumstances. In order to provide a clearer notion of this concept, let's introduce the following notation:

a_{ij}: path gain between the ith mobile and the jth base station.

H_{ij}: QxQ (non-negative) normalized link gain matrix, where $h_{ij} = a_{ij}/a_{ii}$ for $i \neq j$ and $h_{ij} = 0$ for $i = j$

In [3] it has been demonstrated that ρ has an upper bound given by

$$\rho^* = \frac{1}{\gamma^*(H)} \tag{1}$$

where $\gamma^*(H)$ is the dominant eigenvalue of matrix H. Therefore, we come to the conclusion that the maximum achievable SINR ρ^* depends on the spatial distribution of the mobile stations.

The Autonomous SINR Balancing Algorithm has been simulated considering two different approaches concerning the ρ parameter. Initially it was assumed to be constant and afterwards it was dynamically updated according to equation (1). This second approach received the denomination of Ideal SINR algorithm (Ideal SINR PC), which, for comparison purposes, does not require that power limitation or discretization be imposed at this point.

Autonomous SINR Balancing Algorithm

This algorithm, originally described in [4], considers the noise power only at the receiver. Therefore, the signal-to-interference (plus noise) ratio $\rho_i(t)$, at the instant t, perceived by the ith mobile station is

$$\rho_i = \frac{a_{ii} p_i(t)}{\sum_{j \neq i} a_{ij} p_j(t) + \nu} \tag{2}$$

where:

p_i denotes the power transmitted by the ith base station intended to the ith mobile.

ν denotes the power of the additive noise at the receiver.

In the autonomous SINR balancing algorithm, the ith base station modifies its signal-to-interference (plus noise) ratio, $\rho_i(t)$, in order to approach the desired ρ by an amount proportional to the difference between ρ_i and ρ. This dynamics can be formulated as [4]:

$$\dot{\rho}(t) = -\beta[\rho_i(t) - \rho] \qquad i = 1, 2, \ldots, Q \tag{3}$$

where β, ($0 < \beta \leq 1$), is the proportionality constant. It is straightforward to see that this dynamics cannot stop until $\rho_i(t) = \rho$ for each link i, which confirms that this algorithm balances all ρ_i.

Assuming that the interference power at the ith mobile station remains constant, we have:

$$\dot{p}_i(t) = -\beta\{p_i(t) - \left(\frac{\rho}{a_{ii}}\right)[\nu + \sum_{j \neq i} a_{ij} p_j(t)]\} \tag{4}$$

Rearranging (3) in the form of a difference equation:

$$P_i(k+1) = (1-\beta)P_i(k)[1 + \frac{\beta}{(1-\beta)} \cdot \frac{\rho}{\rho_i(k)}] \tag{5}$$

where $P_i(k)$ and $\rho_i(k)$ represent the power and the SINR, respectively, at the discrete times $k = 0, 1, 2, \ldots$.

In [4] it is demonstrated that the convergence of this algorithm is faster when $\beta = 1$. Equation (5) can therefore be written as:

$$P_i(k+1) = P_i(k) \frac{\rho}{\rho_i(k)} \tag{6}$$

Again, it is important to emphasize that this algorithm will not converge for all values of ρ. A suitable value must be chosen, so that equation (3) can reach the equilibrium for all radio links.

Signal-level-based Power Control

This algorithm was originally proposed in [5], and it is based on the criterion of minimizing the outage probability, which is defined as the probability that the signal-to-interference ratio SIR_i, at a certain link, be below a minimum threshold ρ_0. This approach assumes that the mean value of the signal-to-interference ratio (SIR_i) remains constant. Consequently, if the SIR_i variance is minimized, the outage probability will decrease. The goal is then to choose a power control function minimizing the SIR_i variance, which must be based only on the path gain a_{ii} [dB] of the corresponding link, since we desire a completely distributed power control.

$$p_i = f(a_{ii}) \tag{7}$$

In [5], it has been shown that the function minimizing the SIR_i variance is a linear function given by:

$$P_i = -\frac{1}{2}a_{ii} + k \ \ \text{[dBm]} \tag{8}$$

where k is a constant.

III. Simulation Model

The simulation approach adopted in this work consists of snapshot analyses on the system-level followed by the mapping of link quality (SINR) results into quality of service (bit rate) figures. The same methodology was also used in [6] for estimating the performance of data services in GSM networks. The transposition of SINR into throughput values is based on link-level simulation results from [7] for a non-hopping TU50 interference-limited scenario. Fig. 1 shows the throughput performance of EDGE's nine modulation and coding schemes (MCSs) for the referred scenario.

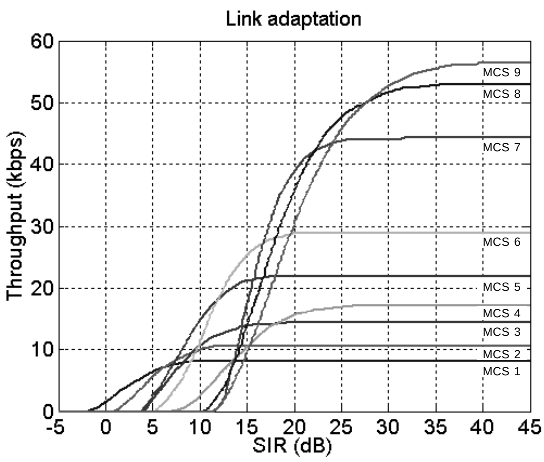

Fig. 1. Throughput for TU50, no frequency hopping, and interference-limited scenario.

We assume ideal LA operation in that the MCS maximizing a given link quality is always chosen. Only the downlink is evaluated, since this is expected to be the limiting link direction in 3G data communications.

Power control in GERAN has been specified for both the base station (BS) and the mobile station (MS) [8, 9]. For the MS the implementation of power control is mandatory, while for the BS it remains an option. Downlink power control, according to [8] and [9], assumes discrete values. The range over which the base station is capable of reducing its RF output power from its maximum level is nominally 30 dB, in 15 steps of 2 dB. Thus, as long as the maximum output power is defined, the minimum output power and all possible output power levels become automatically determined. Assuming these constraints, the examined algorithms have been appropriately modified in order to provide discrete power levels.

In the downlink case, the power control is performed in the BS, which must have at its disposal information concerning the radio link performance. Therefore, MSs have to transfer Channel Quality Reports to the BS [10]. Such reports are sent through the Slow Associated Control Channel (SACCH), which leads to delays and imprecision in the power control scheme. Throughout this work it is assumed that the BS is informed about the channel conditions at every iteration, which, according to [11], results in more optimistic values (approximately 1 dB in [11]).

In GERAN, when applying dynamic allocation in the uplink, MSs are dynamically assigned to transmit in the reverse channels. The indication of which MS will have access to the uplink channel at the next block(s) is carried by the Uplink State Flag (USF). This flag consists of a field defined within the Radio Link Control (RLC) blocks transmitted in the downlink. By monitoring these transmissions the MSs are able to determine when they may access the reverse link. Thus, the network must ensure that the downlink output power level be high enough to reach the MS for which the RLC block is intended, as well as the MS(s) for which the USF is intended, allowing for the correct functioning of the uplink access mechanism [10].

In order to analyze the impact of this constraint over downlink power control performance, we studied the case where MSs waiting for RLC blocks and for the USF are present in the system. In such scenarios, the MS with the worst initial channel condition, which can be expecting either an RLC block or a USF, is selected to guide the power control algorithm at the corresponding BS.

The performance at the 10th percentile of the measures is used as the QoS criterion throughout this work.

In order to conduct the proposed analyses, a system-level simulator has been implemented. It consists of a set of co-channel base station sectors, orderly arranged over a 1/3 frequency reuse pattern cellular grid. According to results presented in [12], this reuse provides better spectral efficiency for packet switched data traffic than 3/9 and 4/12 reuses under the same conditions. The grid is comprised of two layers of interferers, base stations are located in the corner of the sectors, and the employed sector antenna radiation pattern comes from [13].

A snapshot analysis consists of 2000 independent trials. Each trial, a number of mobile stations is uniformly distributed over the system area, long-term fading (shadowing) figures are drawn, and power control, if active, is performed for a number of iterations, while all other system parameters are constant. Afterwards, the performance of the MSs is collected for analysis.

For simulations disregarding USF constraints, one MS is placed within each sector. These MSs are assumed to be expecting RLC block data. As for simulations involving USF analysis, two mobiles per sector are considered instead, one expecting RLC blocks (RLC MS), and the other expecting USF information (USF MS). Within this scenario, at the initial iteration, the MS (RLC or USF MS) verifying the worst signal level is selected to guide the adaptation procedure of the PC algorithms. It is expected that the coverage for the MS in the worst condition will also satisfy the power requirements of the better positioned MS, even though link quality guarantees are not provided. For the scenarios without power control the BS transmission power is set to its maximum value. The most important simulation parameters are shown in table 1.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
System Parameters	
Number of trials	2000
Frequency reuse	1/3
Base Station Antenna System	3-sectored [13]
Sector radius	500 m
Data transfer direction	Downlink only
System frequency	2,000 MHz
BS antenna height	15 m above rooftop
MS height	1.5 m
Path loss model	Vehicular [13]
Frequency hopping	Not employed
Shadowing standard deviation	6 dB
Thermal noise density	-174 dBm/Hz
Link adaptation	Ideal (no delays and SINR is known a priori)
Maximum transmission power	35 dBm
BS antenna gain	13 dBi
BS losses	2 dB
Transmission power adaptation step	2 dB
Transmission power levels	15
MS data terminal gain	2 dB
SINR PC	
Convergence iterations	40
SINR target ρ	6 dB
Signal-level-based PC	
Convergence iterations	Immediate adjustment
k	-25 dBm

IV. RESULTS

In this work we assume as QoS criterion the 10^{th} percentile of both the throughput and SINR. The studied power control algorithms intend to promote QoS gains, which can be translated into capacity gains. The parameters ρ and k, for the autonomous SINR balancing and signal-level-based algorithms, respectively, were determined through several simulations, in which the optimization of the 10^{th} percentile throughput was a priority. The results show that both power control strategies improved the 10^{th} percentile of the SINR, when compared to the case without power control. It can be seen in Fig. 2 that SINR PC with ρ = 6 dB achieved the best performance, followed by the signal-level-based algorithm.

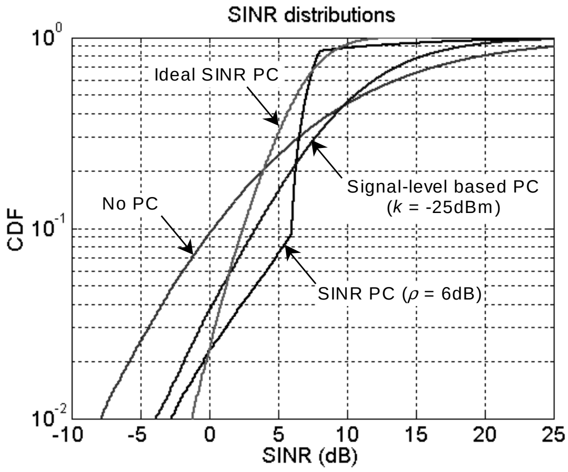

Fig. 2. SINR distributions with and without power control.

The autonomous SINR balancing algorithm forces the SINR of all MSs to converge to ρ. As a result it is expected that the SINR variance reduction of each link (and consequently of the system SINR as a whole) promoted by this algorithm be greater than the reduction achieved by the signal-level-based algorithm.

According to the methodology described in section III, the SINR distribution was mapped to throughput values by making use of the link adaptation curves presented in Fig. 1. The resulting distributions are shown in Fig. 3. The gains verified with the use of power control (Fig. 2) have been translated, as expected, into throughput gains. We observe that the QoS gain at the 10^{th} percentile, when employing the SINR PC, is higher than 240%. Using signal-level-based PC a QoS gain of approximately 145% can be reached. Such gains may be translated into capacity gains by allowing more users to enter the system until the 10^{th} percentile of the throughput reaches once more the QoS requirement. For future works, a more detailed study will be conducted, with the purpose of estimating the achievable capacity gains by using downlink power control in EGPRS under dynamic simulations.

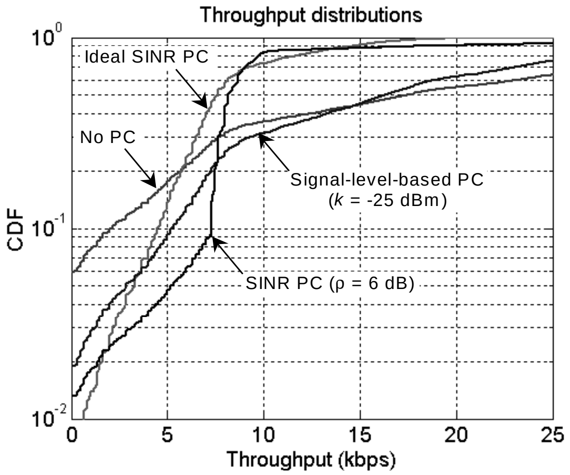

Fig. 3. Throughput distribution with and without power control.

Since the algorithms try to balance the quality of the radio links (the SINR PC balancing the SINR of the links around ρ and the signal-level-based PC adjusting the received power around k), QoS gains are achieved at the cost of the reduction of the mean system throughput. Table 2 presents the 10th percentile and the mean system throughput. The results are presented considering 95% confidence intervals.

TABLE II
THROUGHPUT RESULTS

Metric (Kbps)	**No PC**	**Ideal SINR**	**Signal-level-based (k = -25 dBm)**	**SINR (ρ = 6 dB)**
Throughput at 10th perc.	2.13 (± 0.23)	4.49 (± 0.13)	5.22 (± 0.11)	7.31 (± 0.02)
Mean throughput	21.0 (± 0.23)	8.54 (± 0.08)	18.00 (± 0.23)	10.82 (± 0.24)

Fig. 2 and Fig. 3 present curves for the Ideal SINR algorithm. Analyzing the results, we observed that the Ideal SINR PC performs worse than the SINR PC using a fixed ρ value. This is comprehensible, since the entire set of MSs will always converge to the maximum achievable SINR. If a mobile perceives very bad channel conditions, then all other mobiles in the set will have their SINR performance reduced, in order to maintain the balance [3]. Based on the simulation results, we have verified that it is better to use a fixed ρ value, optimized for each simulated scenario.

When the power constraints for USF reliable reception are introduced into the system, the performance of the studied power control algorithms is degraded. Figs. 4 and 5 show that the gains provided by the power control algorithms are significantly reduced when the referred constraints are imposed. In this new scenario the power control algorithm parameters can be optimized to achieve higher QoS gains. We found that the SINR PC algorithm performs slightly better ρ = 4 dB than with ρ = 6 dB, reaching 5 Kbps of throughput at the 10th percentile, when considering the USF constraints. For the signal-level-based algorithm, a k value of –25 dBm presented the best performance in terms of 10th percentile throughput, even when subjected to the USF restrictions. In this case, a bit rate of approximately 4 Kbps is verified at the 10th percentile. Anyway, its performance remains below the one achieved when disregarding USF constraints.

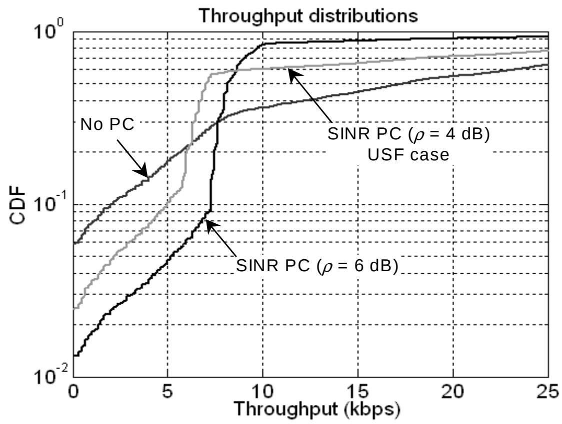

Fig. 4. Throughput distributions for SINR PC with and without USF constraints.

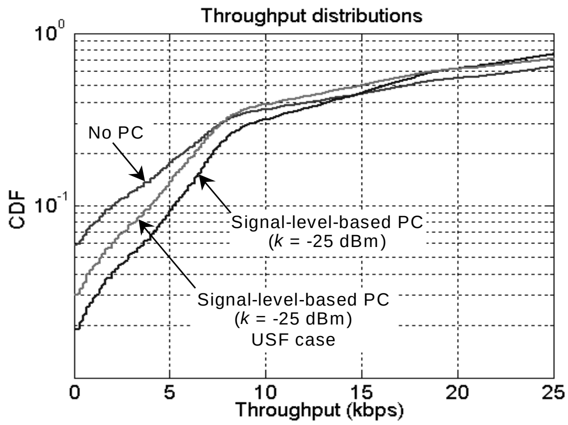

Fig. 5. Throughput distributions for signal-level-based PC with and without USF constraints.

IV. CONCLUSIONS

We have described a methodology for estimating the performance of power control in the packet data service of the GSM/EDGE radio access network, EGPRS. Two PC algorithms have been evaluated with respect to the mean throughput and the 10th percentile of data throughput, defined here as the relevant QoS criterion. Signal-level-based PC is an open-loop algorithm, while SINR PC is closed-loop. SINR PC outperforms the signal-level-based PC algorithm at the cost of implementation complexity and slower algorithm convergence. Both algorithms require optimization of parameters, which are dependent on issues such as the specific scenario and propagation effects. It has also been shown that PC performance deteriorates significantly when USF reception must be taken into account. Furthermore, it should be noted that the snapshot analysis performed here reflects instantaneous states of a dynamic system and may not necessarily yield good estimates of other QoS metrics, such as the widely adopted 10^{th} percentile of the mean packet throughput per user. This investigation may be the subject of future works.

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