Analyzing signal strength versus quality levels in cellular systems: a case study in GSM.

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Abstract—The authors propose a new tool to analyze the performance of a cellular base station. The analysis is based on the joint processing of the received power and quality measurements, both in the uplink (UL) and the downlink (DL). These measurements are originally designed for power control and handover purposes. The main objective of the paper is to fully describe and, therefore, to detect situations involving abnormal interference levels in UL and DL. These situations can be a consequence of a malfunctioning of the power control algorithm, a bad radio optimization and planning or the presence of an outer interference, among others. The novel tool proposed is valid for any cellular system, in this paper we focus on its application to GSM/GPRS system to illustrate its benefits. We include some experiments where real cell data recordings were analyzed.

I. INTRODUCTION

This work provides tools to implement a fast monitoring method of the performance of a cell in terms of power efficiency and interference control. This is a crucial issue in radio network optimization. At the present, it is based on simple parameters like signal strength, handovers and call falls. These methods are inefficient in some situations. For example, they may not detect if a cell is suffering an interference unless the traffic is affected significantly.

In this scenario, a novel method to analyze cellular radio network measurements is presented. It is based on the joint processing of power and quality measurements for both uplink/downlink connections\(^1\). Signal strength and quality measurements are typically designed for purposes of power control and handover but methods for processing these measurements with other targets have been proposed. Measurements in GSM/GPRS can be used for the optimization of handover algorithm\(^1\), an estimation of the Carrier to Interference ratio\(^1\)\(^2\), user positioning methods\(^1\),\(^3\),\(^4\) and UMTS planning and RRMM evaluation\(^4\). For UMTS/CDMA, similar works in this line can be found: in\(^5\) a call admission procedure based in SINR measurements is presented and, in\(^6\), an estimation of received SINR is improved by using power control measurements.

The method proposed in this work uses power and quality measurements taken from any cellular system. Therefore, it does not require dedicated measurements or hardware modification, providing a non invasive tool that supplies some relevant evidences on the abnormal behavior of a cell. This strategy is useful, as the wireless communication operator may make quick decisions on the optimization of the power control algorithm, handover strategy or frequency planning. Particularly, we focus on the detection of illegal activities such as jamming. In the following, we pay attention to GSM/GPRS cellular system framework. In the experimental section, we present results based on real GSM/GPRS cell recordings. It is shown that a frequency jammer in a cell can be easily detected. The extension of this approach to any other systems such as UMTS or WiMAX is somehow immediate.

II. MEASUREMENTS

The proposed study of a cell is made only with four parameters: the received power level and the received quality level in both uplink (UL) and downlink (DL). All of them are made in the same carrier or transceiver (TRX). Both base station (BS) and mobile station (MS) are periodically measuring these levels but they are usually processed in the BS. Therefore, the MS has to send its measurements through the signaling channels periodically. Previously, measurements are averaged, quantified and encoded in a discrete number of levels. We denote the resulting signal strength parameter in UL and DL as \(RXLEV\_UL\) and \(RXLEV\_DL\) and the encoded quality parameter in UL and DL as \(RXQUAL\_UL\) and \(RXQUAL\_DL\) respectively. After the average period, the BS has a group of four measurements for each active user, which we propose to jointly process. They are referred as measurements at time \(t\) for the \(i\)-th user.

A. Power level in the BS-MS radiolink

We first study the parameters \(RXLEV\_UL(i)\) and \(RXLEV\_DL(i)\) at time \(t\), where \(i\) denotes the \(i\)-th user. These parameters encode the signal strength levels in the up-link, \(RX\_UL(i)\), and down-link, \(RX\_DL(i)\). Hereafter, upper-case letters denote power levels in dBm while lower-case is used for values in mW. If frequency hopping (FH) is used, the resulting parameters are the average over all frequencies involved.

The BS measures the values for \(P_{RX\_UL(i)}\), but the values for \(P_{RX\_DL(i)}\) are the ones received from the MS. It is not immediate to compare these two values, as the transmitted powers may be different if the control power processes in the UL and the DL have worked in different ways. Also, the received powers grow with the interference level and it can be unbalanced between both links. The proposed method is aware to unbalanced interferences and power control effects.

Received power measurements are processed as follows. The BS knows its transmitted power, \(P_{TX\_UL(i)}\) and the one of the MS, \(P_{TX\_DL(i)}\), dictated by the UL power control algorithm. An estimation of the propagation losses can be performed for both UL and DL as

\[
\tilde{I}_{UL} = \frac{P_{RX\_UL(i)}}{P_{TX\_UL(i)}},
\]

\[
\tilde{I}_{DL} = \frac{P_{RX\_DL(i)}}{P_{TX\_DL(i)}}.
\]

\(^1\)reverse/forward in U.S.A.
In order to compare the estimated propagation losses for both links, its rate is computed:

\[
\gamma = \frac{\Gamma_{UL}}{\Gamma_{DL}} \quad \Gamma = 10 \log_{10}(\gamma).
\]

(2)

By reciprocity of the radio channel, it is assumed that \(\Gamma \sim \delta \) dB, up to a \(\beta \) dB offset if diversity is used in just the UL at reception. Any unbalanced interference between UL and DL deviates \(\Gamma\) from this range as the measured received power is higher. More comments on the influence of interference and power control processes can be found later in this paper.

B. Quality level in the BS-MS radiolink

We now pay attention to the quality parameters \(RXQUAL_{UL}(i)\) and \(RXQUAL_{DL}(i)\) at time \(t\) where again \(i\) denotes the \(i\)-th user. We aim to jointly process the information provided by the \(RXLEV\) and the \(RXQUAL\) parameters. First, quality parameters are rewritten in terms of a normalized power to interference and noise ratio (\(STINR\)) \(^2\). In some systems such as UMTS [7], the quality parameters are quite related to the \(STINR\). However, in others, these parameters are a function of the bit or symbol error rate. In GSM/GPRS, the quality parameter encodes a bit error rate (BER) \([7]\) and an estimation process of the \(STINR\) is required. Once we get an estimation of the normalized signal to noise ratio in UL, \(\sinr_{UL}\), and in DL, \(\sinr_{DL}\), it is defined

\[
\begin{align*}
C_{\text{sinr}} &= \sinr_{DL} \\
C_{\text{sinr}} &= 10 \log_{10}(C_{\text{sinr}}).
\end{align*}
\]

This parameter, along with the estimated propagation losses rate \(\Gamma\), proof to be useful in the study of BS-MS connections, as explained next.

C. Connections between power and quality parameters

Power Control (PC) operates independently in both UL and DL, trying to get acceptable quality levels with the minimum possible transmitted power, which is discretely modified if necessary. In a clean cell, or when both links are equally interfered, if the receivers at UL and DL have similar performance, the measured quality levels tend to be equal in both links, \(C_{\text{sinr}} = 0 \) dB, and so do the transmitted powers, \(\Gamma \in [0, \beta] \) dB. In this scenario, measurements with \(C_{\text{sinr}} \neq 0\) and \(\Gamma \in [0, \beta]\) can also be due to the latency of the control power algorithm, as it usually modifies the power by discrete steps. Therefore, these situations are time limited as the increase of the transmitted power will bring \(C_{\text{sinr}}\) again to 0 dB. Power control algorithms are disabled when the power strength and quality levels decrease below certain thresholds, to limit the interference to neighbor cells [8]. Below these thresholds, there exists no mechanism to get similar quality levels in both links and, therefore, \(C_{\text{sinr}}\) can be far from the ideal 0 dB value for an arbitrary long time, \(\Gamma\) should move around \(\delta, \beta\) dB.

Parameter \(\Gamma\) is useful to detect unbalanced interferences between both links, as there is an increase of the received power that makes \(\Gamma\) deviate from the standard range \(\delta, \beta\) dB. There also exist a quality degradation in the interfered link, so \(C_{\text{sinr}} \neq 0\) dB. Power control processes, if they are enabled as discussed above, increase the transmitted power and \(C_{\text{sinr}}\) tends to 0 dB if the encoding of the measurements for \(\sinr\) are quite insensitive at high values, as it is usually the case. \(\Gamma\) will also decrease if the received signal strength is high enough to hide the interference level. Power controls can not deal with interferences if the maximum transmitted power has been reached. In this situation, \(\Gamma\) and \(C_{\text{sinr}}\) can be arbitrarily high.

D. Application to GSM/GPRS system

In this section, we now focus in the GSM/GPRS system measurement process. In the experimental section, real GSM/GPRS cell recordings are analyzed. In the UL, see Fig. 1, the BS measurements are averaged for each slot every 480 ms in GSM, which is the time to receive a full GSM SACCH packet, 4x26 GSM frames. In GPRS, measurements are averaged in every received radio block. In the DL, the MS averages signal strength and quality levels in the traffic slots of the DL and send them in the SACCH channel every 480 ms in GSM and also in PACKET ACK/NACK messages in GPRS [7]. It is important to remark that the four measurements, which are jointly processed, are not made simultaneously since the UL and DL frames in GSM have a constant delay of three slots (1 ms approx), in order to avoid simultaneous reception and transmission at the mobile station. The channel coherence time considered is around 4.8 ms.

In the GSM/GPRS standard, the quality parameters encode and average the bit error rate (BER). The BER is computed after the channel decoding. In the BS, the BS-MS connections, as explained next.

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### III. ANALYSIS OF REAL GSM/GPRS SITUATIONS

In the following we analyze several connections where the measurements have been collected from real GSM/GPRS base stations. We have studied BTS records taken from two different cells. One of them is low traffic and very clean in terms of interference. The other is a dirty cell with a severe interference radiated by a frequency jammer. Isolated voice connections are studied for both cells using a representation of the estimated losses rate $\Gamma$ (dB), versus the quality ratio, $C_{\text{sinr}}$ (dB). Then, the same experiment is extended to all the connections in the same cell during a period of 10 minutes. We show that an automatic implementation of a method that analyzes the state of a given cell can be designed, as discussed in the next section.

#### A. Voice connections in a low interference environment

We first study a cell with low interference level. A connection that is successfully controlled by the power control (PC) is denoted in the following as controlled connection. In Fig. 2, we include the estimated losses rate, $\Gamma$, versus the quality ratio, $C_{\text{sinr}}$, for a controlled connection. The points have been classified into three groups: points around $C_{\text{sinr}} = 0$ dB ($\triangle$), with $C_{\text{sinr}} > 0$ dB ($\circ$) and with $C_{\text{sinr}} < 0$ dB (□). PC algorithms set good quality levels in both UL and DL and, therefore, most of the points have $C_{\text{sinr}} = 0$ dB. In Fig. 3, the evolution along the time of the transmitted and received power levels and $C_{\text{sinr}}$ parameter is plotted. Although power control processes are independent in UL and DL, they converge to equal power and quality levels. There are a few points with $C_{\text{sinr}} \neq 0$ dB that represent transition points for the power control processes.

Now we pay attention to the points with abnormal high $\Gamma$ values. These points take place when a fast change of the radio path happens, making the measures temporally shifted because UL and DL measurements are made with a delay of 1 ms. In Fig. 4 the evolution of the estimated losses in UL and DL is plotted. Although they follow the same tendency, the losses for the UL may precede the ones for the DL at some instants. However, it does not have a great impact except for a few points, since the delay between UL and DL frames is lower than the coherence time of the channel.

In the same scenario, we now illustrate in Fig. 5 the behavior of a voice connection denoted as non-controlled connection since power control is disabled. There is no mechanism to force equal quality levels in both UL and DL, which explains the higher values of $C_{\text{sinr}}$. As we can observe there exist points with $C_{\text{sinr}} > 0$ dB, $C_{\text{sinr}} = 0$ dB and $C_{\text{sinr}} < 0$ dB randomly distributed.

#### B. Voice connections in a high interference environment

In this case, we analyze a cell where a frequency jammer is present. The interference is strong and unbalanced between UL and DL. Mobile stations that are close to the base station transmit with low power levels and, in case of interference, power control processes
have a margin to increase the transmitted power. An example is illustrated in Fig. 6. Usually, these connections, compared to the one presented in Fig. 2 for a clean cell, have a higher density of points out of $C_{\text{sinr}} = 0$ dB. This is a measurement of the effort that power control processes have to make in order to get similar quality levels in both UL and DL. Besides, $\Gamma$ reaches high values. Notice that quality levels are saturated when $\Gamma$ is high, and $C_{\text{sinr}} = 0$ dB.

An unbalanced interference also provokes a different behavior between UL and DL power control processes. It is illustrated in Fig. 7, where the transmitted and received power levels and $C_{\text{sinr}}$ parameter are plotted for another connection in this cell. The DL suffers in this case a higher quality degradation than the UL and, hence, $C_{\text{sinr}} < 0$ dB. Power control in DL increases the transmitted power to achieve $C_{\text{sinr}} = 0$ dB. Notice that the received power level is specially high in the DL compared to the ones in Fig. 3 for a clean cell.

Due to the presence of the interference, there is a large number of connections where power control processes have reached the maximum transmitted power and they can not guarantee acceptable quality levels. We refer to them as power saturated connections. An example is illustrated in Fig. 8. It is interesting to remark the high $\Gamma$ values obtained with respect to the non controlled connection described in Fig. 5.

Fig. 6. Dispersion graph depicting the estimated losses rate $\Gamma$ (dB) versus
the parameter $C_{\text{sinr}}$ (dB) of a controlled connection in a high interference
environment. The points have been classified: $C_{\text{sinr}} = 0$ dB (△), with $C_{\text{sinr}} > 0$ dB (○) and with $C_{\text{sinr}} < 0$ dB (□).

Fig. 8. Dispersion graph depicting the estimated losses rate $\Gamma$ (dB) versus
the parameter $C_{\text{sinr}}$ (dB) of a power saturated connection in a high interference
environment. The points have been classified: $C_{\text{sinr}} = 0$ dB (△), with $C_{\text{sinr}} > 0$ dB (○) and with $C_{\text{sinr}} < 0$ dB (□).

Fig. 7. Transmitted and received power levels and $C_{\text{sinr}}$ evolution for a
controlled connection in a high interference environment.

IV. AUTOMATIC ANALYSIS TOOL

The measurement processing method proposed must be pro-
grammed in a computer in order to incorporate them to commercial
mobile optimization network software. The software must be able not
only to process the measurements, but also to make decisions about
the conditions of a particular cell. This implies to design algorithms
and thresholds. Working with dispersion graphs that compares $\Gamma$
parameter versus $C_{\text{sinr}}$ is not enough as information about density
of points is lost. In this section, we include this information depicting
a 3D histogram for each cell in sections III-A and III-B with several
controlled and power saturated connections during an analysis period
of ten minutes. The results will are sufficiently clear to give a simple
version of a method to classify the state of a GSM/GPRS cell.

In Fig. 9 the results obtained for the low interference cell are
included. Points are mainly concentrated in the $\Gamma \leq 5$ dB and
$C_{\text{sinr}} = 0$ dB region. These good results are a consequence of a
correct performance of power control processes. Low $\Gamma$ values are
evidences of a clean environment. Out of the $C_{\text{sinr}} = 0$ line the
density of points is very low: power control processes have worked
well in a few steps. This is also a proof of the good conditions
of the cell.

The same experiment for the cell with the frequency jammer
is included in Fig. 10. Differences between both figures are clear. First, $\Gamma$ values are not limited to $\Gamma \leq 5$ dB. There exist a lot of measurements up to 10 dB as a consequence of the unbalanced interferences. The distribution of points with $C_{\text{sinr}} \neq 0$ evidences the presence of interference or, eventually, a malfunctioning of the PC. The increase of connections where PC can not deal with the interference explain the higher density of points in this region.

By observing the two previous figures, we can establish simple rules for a GSM/GPRS cell classification method. Only controlled connections have been included in the histogram. Four regions must be studied:

A. Optimal Power control region. Measurements with $C_{\text{sinr}} = 0$ dB and $\Gamma \leq 5$ dB. They are typical in connections properly controlled by PC algorithms in clean environments. This region is the objective of any PC algorithm and cellular planning.

B. Low interference region with quality degradation. Measurements with $C_{\text{sinr}} \neq 0$ dB and $\Gamma \leq 5$ dB. These points are due to PC transitions.

C. Interference region with quality saturation. Measurements with $C_{\text{sinr}} = 0$ dB and $\Gamma > 5$ dB. If signal level is near to the interference, the difference in the losses is large. However, if the received levels are large enough, both links achieve the best quality. They may also be a consequence of a shift in the measurements in UL and DL.

D. Interference region with quality degradation. Interference in UL and DL makes $\Gamma$ grow and forces a quality degradation.

In the clean cell, the points are almost exclusively in region A. It is expected a low density of points in C and D regions. On the other hand, in a cell with a high unbalanced interference, the points are mainly distributed through C and D regions. Hence, a frequency jammer that only radiates in one of the two links can be quickly detected.

To design a detection algorithm, the histograms could be easily translated into probability density functions with any off-the-shelf technique. By, e.g., approximating them by a bi-dimensional Gaussian density function. The estimated means and variances could be used to design an algorithm to detect anomalies. In this sense, more real records could be of interest to better design appropriate thresholds. Also, records of cells with high interferences in both links are needed to characterize and detect these situations.

V. Conclusions

The proposed representation of the power level and quality measures in a wireless cell system provides a better overview of its behavior in terms of interference and quality requirements. Any steady-state abnormality can be easily detected if the measurement distribution presents a high difference in the propagation losses for UL and DL, or different qualities in both links. Also, and most important, the distributions of the points of this representation could be useful to detect unbalanced interferences. Overall, the tool allows detects, among others, a strong interference, a bad performance of the power control, a poor radio planning and a non-desired outer jamming. This novel interference analysis tool has not hardware requirements since it takes the signal strength and quality measures that are usually available in every wireless network, typically for control power processes. The good performance of this novel analysis has been illustrated with real data from a commercial mobile GSM/GPRS network, but can be extended to other wireless systems as UMTS and WiMax.

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