Advanced Power Control for UTRAN LTE Uplink

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A thesis submitted for the degree of
Master of Science

June 19th, 2008

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TITLE: Advanced Power Control for UTRAN LTE Uplink
THEME: Mobile Communications
PROJECT PERIOD: 10th Semester, October 2007 to June 2008
PROJECT GROUP: 1121

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COPIES:
3
NUMBER OF PAGES:
95
FINISHED:
June 19th, 2008

Abstract

Single Carrier Frequency Division Multiple Access (SC-FDMA) is the access scheme chosen by 3GPP for uplink UTRAN Long Term Evolution project. As SC-FDMA provides intra-cell orthogonality, one of the main reasons for performance degradation is the inter-cell interference.
This degradation is accentuated by the frequency reuse factor of 1 deployed in the system, which makes the Power Control (PC) functionality a critical issue. Recently, a PC formula containing an open loop and a closed loop component has been standardized. The open loop power control (OLPC) compensates for slow varying pathloss and shadowing, while the closed loop power control (CLPC) implementation is vendor specific and still under research. It allows to compensate for fast variations and manage the interference.
In this thesis, the OLPC is studied in detail to obtain a reference performance, then two CLPC techniques are proposed with the aim of improving it. All techniques are implemented on a static simulator that models slow variations. The comparison of the result among the different techniques is carried out by considering key performance indicators like the cell outage and cell throughput The results show a gain compared to the OLPC of up to 22 % of in outage user throughput with a 5 % in cell. Alternatively, it is possible to tune the parameters of the proposed techniques to obtain more gain in cell at the cost of a reduction of the gain in outage.

Preface

The present document summarizes the work carried out at *Aalborg Universitet* as Master Thesis by Nestor Jesus Quintero, Telecommunication Engineering student from the *Universitat Politecnica de Catalunya.* The thesis has been conducted at the facilities of *Nokia Siemens Networks* Aalbrog from October 2007 to June 2008.

Acknowledgements

First of all I would like to thank my supervisors, Francisco Davide Clabrese and Claudio Rosa, for all the care and effort they invested in me from the first day until the end. I have learned a lot from you. Many thanks goes for all *Nokia Siemens Networks* and *Aalborg Universitet* people, thanks for lending me your facilities, for sharing your expertise and for the nice work environment. Thanks for the economic support as well.

I am grateful to all those who have supported me during my stay in Denmark. I thank also those whose selfishness has made my experience outside Venezuela tougher, their ego has taught me much. My family and friends in Venezuela and in Spain have my deepest gratitude, always. Merci! to all my new friends in Aalborg, you are special. And finally, thanks to you Agata, I am glad to have met you here.

Aalborg University, 19th of June 2008

Nestor Jesus Quintero Goncalves

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Glossary

PG_S Pathgain to the serving Base Station

PG_S Sum of pathgain to the non serving Base Station

3G 3rd Generation

3GPP 3rd Generation Partnership Project

AMC Adaptive Modulation and Coding Scheme

BER Bit Error Rate

BS Base Station

BW Bandwidth

CLPC Closed Loop Power Control

FPC Fractional Power Control

FTB Fixed Transmission Bandwidth

G-IPC Generalized Interference Based Power Control

GSM Global System for Mobile Communications

HARQ Hybrid Automatic Repeat Request

HO Hand Over

HSPA High Speed Packet Access

IoT It is the interference over Thermal noise

IPC Interference Based Power Control

KPI Key Performance Indicator

LA Link Adaptation

LTE Long Term Evolution

MCS Modulation and Coding Scheme

MRC Maximal Ratio Combining

OFDMA Orthogonal Frequency Division Multiple Access

OLPC Open Loop Power Control

PAPR Peak To Average Power Ratio

PG Pathgain

PL Pathloss

PRB Physical Resource Block

PS Packet Scheduler

psd Power Spectral Density

PUCCH Physical Uplink Control Channel

PUSCH Physical Uplink Shared Channel

RRM Radio Resource Management

SINR Signal To Interference Noise Ratio

SNR Signal To Noise Ratio

TTI Time Transmission Interval

Tx power Transmitting power

UE User Equipment

WA Wrap Around

WCDMA Wideband Code Division Multiple Access

1

Introduction

The collaboration agreement 3rd Generation Partnership Project (3GPP) was established to produce globally applicable Technical Specifications and Technical Reports for a 3rd generation mobile system. The systems are designed to meet evolving data rates and diverse traffic.

1.1 3GPP UTRAN Long Term Evolution project

Several projects within the 3GPP have been undergoing to improve the evolved GSM networks. Their design is based on coexistence: each new system introduces a few new elements and technologies while aiming to reuse the previous network architecture.

The projects technically and chronologically follow the trend of Figure 1.1. Global System for Mobile Communications (GSM) has evolved into Enhanced Data Rates for GSM Evolution (EDGE) while on top of these, Wideband Code Division Multiple Access (WCDMA) technology is introduced, evolving into networks such as High Speed Packet Access (HSPA) [(11)].

Long Term Evolution (LTE) is a system currently under standardization. It has the goals of achieving peak data rates of 100 Mbps in downlink (DL) and 50 Mbps in uplink (UL). It also aims to ensure competitiveness for the next 10 years and beyond. Apart from the increase in peak data rate, some of its requirements are:

- Improve the spectral efficiency, from a factor of 2 up to 4 when compared to HSPA Release 6 [(12)].
- Reduce latency.
- Apply a frequency reuse factor of 1.
- Reasonable system an terminal complexity, cost and power consumption.

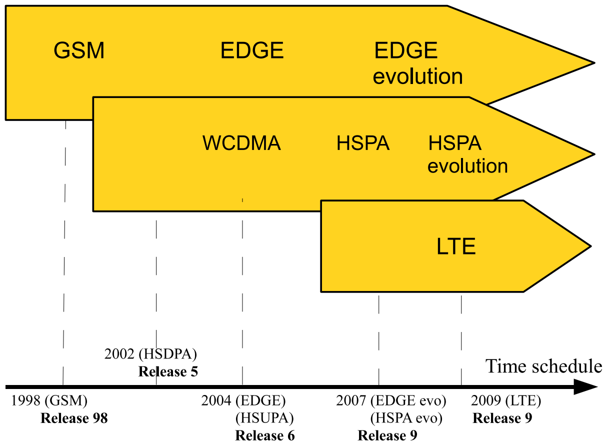

Figure 1.1: 3GPP project Evolution - LTE is planned to coexist with future networks

- Support for inter working with existing 3G systems and non-3GPP specified systems.

Functional and technological changes are introduced with LTE to achieve the goals and demands at hand, for example, the migration to an All-IP network that adapts to the traffic requirements. To achieve this an appropriate radio interface is needed.

Orthogonal Frequency Division Multiple Access (OFDMA) has been selected to be the basic access scheme for DL due to its high immunity to multipath [(16)], its superior spectral efficiency and bandwidth scalability. However, UL is subject to different conditions.

1.1.1 LTE Uplink

One drawback of OFDMA is that it suffers from a high Peak To Average Power Ratio (PAPR) [(12)] that usually requires higher transmission power to maintain a desired Bit Error Rate (BER) . This is a scenario to avoid particularly in mobile handsets since power restrictions are higher. For this reason the scheme chosen for UL is Single Carrier FDMA (SC-FDMA)[(15)] which is a modified form of OFDMA that offers better properties in PARP.

This scheme and the technology deployed in LTE UL allow a highly flexible handling of radio interface resources that make many possibilities available over frequency and time, particularly superior when compared to other systems.

1.1.2 Radio Resource Management in LTE UL

In UTRAN LTE UL the Modulation and Coding Scheme (MCS), the bandwidth, the transmission frequency and the power spectral density used for transmission could be changed as fast as every 1 ms -a Time Transmission Interval (TTI)- , giving the instruments to define powerful functionalities.

Two main entities abstract these: the first is the Packet Scheduler (PS) which is the core entity of the Radio Resource Management (RRM) . It is responsible for a varied of functionalities [(14),(8),(6)]. The second is the Link Adaptation Unit (LA) . A basic structure is illustrated in Figure 1.2.

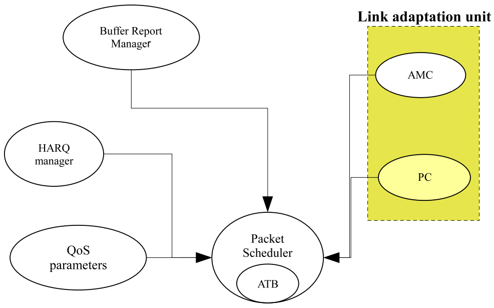

Figure 1.2: Subset of RRM functionalities - Power Control is one of the functionalities of the Link Adaptation Unit and the subject of study of this work

To perform the allocation of resources the Packet Scheduler receives many inputs which come from the Buffer Status Report Manager, the QoS parameters, the Hybrid ARQ (HARQ) manager and the LA unit. The Buffer Report Manager [(5)] gives information about data to be transmitted from users allowing for example, not to give resources to users who have no data to transmit. QoS Parameters [(5)], help to treat the type of data transmitted to give differentiation and/or priority to users. The HARQ manager [1] allows to give priority to users with retransmissions pending. The Adaptive Transmission Bandwidth (ATB) exploits the possibility to change the user transmission bandwidth during its active period in a fast way.

[1]Hybrid ARQ [(4)] is the adopted retransmission scheme in LTE

In the LA, the Adaptive Modulation and Coding Scheme (AMC) [(19)] is used to change the Modulation and Coding Scheme (MCS) deployed in transmission to adapt for channel variations. Potentially, it can select the most appropriate MCS after the PS has allocated a frequency band. Power control (PC) is responsible for managing the transmitting power spectral density (psd) of each user. When it serves as interface with ATB, it coordinates that handset power limitations are conserved when the transmission bandwidth is changed.

It is seen that PC is one of the functionalities in RRM. Its impact is not isolated from the PS but itself at a functional level, is. It is the focus of study in the present work.

1.1.3 Power Control in UTRAN LTE UL

Considering the specific consequences of the use of SC-FDMA, PC in the analyzed system is justified from:

- From the system point of view: the need of a reduced impact of inter-cell interference level.
- From the user point of view: achieve a required Signal To Interference Noise Ratio (SINR) level.

These two are interrelated since the interference is a consequence of the transmitted power,a basic, yet solid fact to bear.

PC works as part of the LA unit with the purpose of controlling the transmitting psd of the users for hazards reason meeting required signal levels with respect to compensation of channel variations typical of mobile communications systems [(20)]. According to which variations of the channel are to be compensated, the schemes are divided in two types:

- Slow power control: designed to compensate for slow channel variations (distance-dependent pathloss, antenna losses, and shadow fading).
- Fast power control: designed also to compensate for fast channel variations (fast fading)

There are two other distinctions of PC schemes related to the properties of the information sent to the mobile to set its power:

- Open Loop Power Control: The power is set at the mobile terminal using parameters and measures obtained from signals sent by the eNode-B (eNB). In this case no feedback is sent to the BS regarding the power used for transmission

- Closed Loop Power Control: The UE also sends feedback to the eNB, which is then used to correct the user Tx power. [2]

Qualifying the PC technique in slow, fast, open loop and closed loop helps to have an anticipated idea of the implementation complexity and expected level of performance. For example, it is presumed that a fast closed loop PC scheme would require high signal overhead of transmission but at the same time it would provide with a fast mechanism to compensate for interference and channel conditions. On the other hand, a slow open loop PC would result in simpler implementation and low signaling but would be unable to compensate for channel variations for individual users.

A PC formula has been already agreed in a 3GPP meeting [(17)] in June 2007 where PC in LTE UL is expected to include both open loop and closed loop terms. It is understood that the main scope of PC in LTE UL is to compensate for slow varying channel and potentially for interference conditions, while other mechanisms (i.e. fast AMC) should adapt to fast variations.

However, while the formula has been agreed, the algorithms that define the use of the closed loop term remains open. This and the inter-cell interference condition, both illustrated in Figure 1.3 set the starting point for the present work. Also the fact that PC should compensate for slow channel variations only.

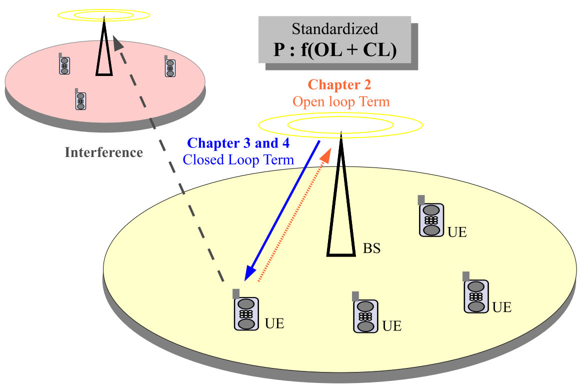

Figure 1.3: Power Control Working Scenario - Standardized PC includes an open loop and a closed loop term. The main interference is inter-cell.

[2]GSM networks for instance, proposed Closed Loop Schemes [(11)] where the UE, starting from minimal power, sends notifications to the node if its BER is below target with the purpose of powering up.

1.2 Objectives

It is known at this point that the subject of study of the work is PC. now the available work on the subject is over viewed, to concretely state the scope of the thesis and the way it is assessed.

1.2.1 State of the Art

Specifically about PC, available work covers the open loop term, with an evaluation of its initial performance and capabilities, [(9)]. Other work explores the first approach of inter work between the PS and PC [(21)], which addresses the interference conditions.

A novel technique to implement with LTE UL PC is proposed in [(7)] where the closed loop term is considered to improve the initial performance of FPC by the means of using information of user's potential generated interference. The research and study of this closed loop term is still on going. The present work takes this point as inspiration and the previous as fundaments to asses the problem.

Besides, some available work studies how the system performs with ATB [(10)] and with AMC [(19)], which serves to give background and make the necessary assumptions.

1.2.2 Scope

The objectives of this work are:

- Study the FPC technique present in the current standardized formula to obtain a reference performance and analysis framework
- Propose different Power Control techniques that provide gain over the previous, which would determine a criteria of how to use the closed loop correction, also detailing aspects that show potential to be subject for future study and work.

1.2.3 Assessment methodology

To fulfill the proposed objectives a simple system model is needed, where the functionalities of PS and AMC (Figure 1.2) are simplified to focus the results on PC.

For this purpose, a simplified static simulation approach has been used which focuses on PC while neglecting the effect of other RRM functionalities such as ATB (Fixed Transmission Bandwidth (FTB) is assumed), channel aware scheduling and retransmissions. The approach consists primarily in taking a "snapshot" of the system where a configuration of users transmits with a certain psd, and proceed to calculate the interference and signal distributions. Details of this approach are found in appendix (A 1)

To evaluate the performance of the starting and proposed techniques a few Key Performance Indicators (KPI) have been chosen:

- **Cell throughput**: It is the total UL throughput of users served by a given cell. In the thesis it all throughputs are considered at link level.
- **X% ile outage throughput**: It is the throughput at the X% point of the Cumulative Distribution Function (CDF) of the user thorughput. It is an indicator of the coverage performance.
- **Interference over Thermal Noise (IoT)** The interference perceived at a cell normalized to the thermal noise level. The normalization is done to compare different results.
- **User SINR, Transmitting Power (Tx power)** distributions of user transmitted power and experienced SINR

The scope of using such KPIs is to provide with a quantitative measure of the gain of a specific PC scheme in terms of system as well as user performance. The first two indicators are usually observed together (Figure 1.4) since they allow to quickly identify where the gain is. Details on calculations of KPIs are found in appendix (A 2).

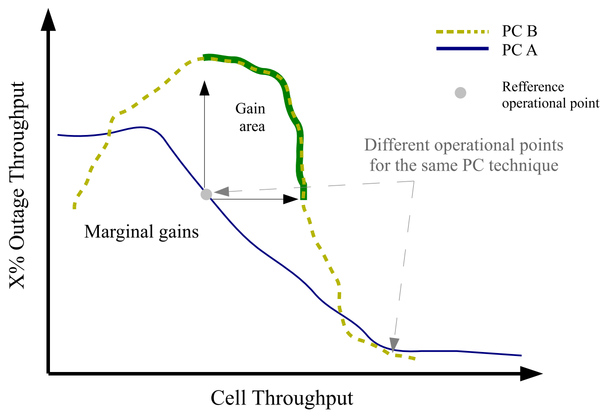

Figure 1.4: Example of performance comparison for PC techniques - Comparing to a reference point of PC technique A, PC B defines an area of both cell and outage throughput

1.2.4 Thesis Structure

The first objective, the study of FPC, has the purpose of giving a reference point and introduce the structure of analysis, reason to take its place in chapter 2. Next objective requires the study of proposed PC techniques that use the closed loop term, this is covered in chapter 3, the Interference Based Power Control. Another technique is proposed and evaluated based on the Interference Based Power Control, on chapter 4 the Cell-IPC, introducing higher gain and complexity. Figure 1.3 illustrates where the core chapters locate in LTE UL Power Control. Finally, the conclusions and future work on chapter 5.

2

Fractional Power Control

This chapter focuses on the Open Loop term of the LTE PC standardized formula.

The interest regards the transmission that takes place in the Physical Uplink Shared Channel (PUSCH) , and Physical Uplink Control Channel (PUCCH) [1] the specifications then, are extracted only for the related Physical aspects.

2.1 LTE UL Standardized PC formula

The PC formula for the PUSCH has already been agreed to be as Equation (2.1). The transmitting power is set at the User Equipment (UE) using parameters received from the eNB and control commands.

$$P = min\{P_{Max}, P_0 + 10 \cdot log_{10}M + \alpha \cdot PL + \delta_{mcs} + f(\Delta_i)\} \qquad [dBm] \tag{2.1}$$

Where:

- P_{Max}: is the maximum power allowed by the terminal. It depends on the UE class
- **M**: is the number of allocated Physical Resource Blocks(PRBs) [(3)]
- P_0: is a parameter that has a cell specific and nominal part. It is measured in dBm, expressing the power to be contained in one PRB
- α: a cell specific parameter
- PL: is the downlink pathloss estimated at the UE
- δ_{mcs}: MCS dependent offset. It is UE specific
- $(f(\Delta_i))$: is a function that permits to use relative, cumulative or absolute corrections values. It is UE specific.

[1]Consequently, the techniques analyzed during this work are meant to be only for these two channels. But the data transmission takes place on them only [(1)]

The physical level specifications can be found in [(4)]. To study the PC techniques some assumptions and simplifications are needed to focus on the link level. The objective is to study the foundation of different PC techniques and later discuss how their implementation adapt to (2.1). These are:

- P_{Max}: Fixed at 250 mW
- P_0: Equal to all cells in the system
- α: Also equal for all cells in the system
- PL: assumed to be equal to the UL pathloss

As a note, these same assumptions are used in reference work [(9), (21)] to obtain results. These pursue the set of a scenario simple enough for the initial evaluation. The results obtained here thus, can be directly compared to them.

The parameters P_0 and α are signaled from the eNB to the UEs as broadcast. Together with the pathloss measure, it is information enough to let the user initially set its transmitting power, reason for why they are recognized as the open loop term. The parameters δ_{mcs} and Δ_i (according to its function) can be signaled to any UE individually as part of the UE grant [(2)], after it sets its initial Tx power according to the open loop term and sends feedback to the eNB. These are the closed loop Terms.

According to this, when any user sets its power for transmission the starting point is the open loop term. It is designed funded on the principle of Fractional Power Control (FPC) , which is studied next in this chapter.

2.2 Fractional Power Control Concept

From the RRM point of view, the scope of PC is to define the transmitting power in one PRB according to Equation (2.1), letting the UE scale it to the assigned transmission bandwidth (BW) . This implies that ultimately it will transmit with a constant power in each assigned PRB, or in other words, it will have a constant power spectral density over the transmission bandwidth.

For this reason, the term $10 \cdot log_{10}(M)$ can be extracted from Equation (2.1) and also, from the RRM point of view the power limitation can be neglected since it corresponds to the UE to respect it.

Finally, removing the closed loop term, the formula results in Equation (2.2), which is referred to as the FPC formula.

$$PSD = P_0 + \alpha \cdot PL \qquad [dBm] \tag{2.2}$$

This equation has the units dBm according to the units of P_0, however, it represents the total power contained in one PRV, and thus, is is referred to -unvirtuously- PSD. This quantity is scaled compared to the conventional definition of Watts per one Hertz (W/Hz) by the bandwidth of one PRB.

Regarding the convention, the expressions written in dB units are shown in capital letters while the linear in non capital. Also, it is preferred to work with the pathgain information which is the linear inverse of the pathloss. Then Equation (2.2) is re-written as Equation (2.3) in dB or as in Equation (2.4) in linear.

$$PSD = P_0 - \alpha \cdot PG \qquad [dBm] \tag{2.3}$$

$$psd = \frac{p_0}{pg^\alpha} \qquad [mW] \tag{2.4}$$

Where PG is the pathgain of the user to the serving Base Station (BS) .

To explore the FPC concept, first the effect of the parameters P_0 and α in Equations (2.4) and (2.3) is studied. It is understood that the system can be simulated once per each pair of them.

It is first remarked that the psd is linearly dependent with p_0, while α weights its dependency with the pathgain. p_0 is constant for all users while the term pg^α varies for each UE according to its experienced pathgain. Attention is drawn to this, since it is the element that will differentiate the users performance.

Figure 2.1 shows the resulting PSD of two different α values for a wide range of PG which correspond to the default simulating scenario. The case $\alpha = 1$ results in a Tx psd that aims to compensate to a user for the degradation caused by the pathgain. The compensation is done allowing it to transmit with more power if such pathgain is lower.

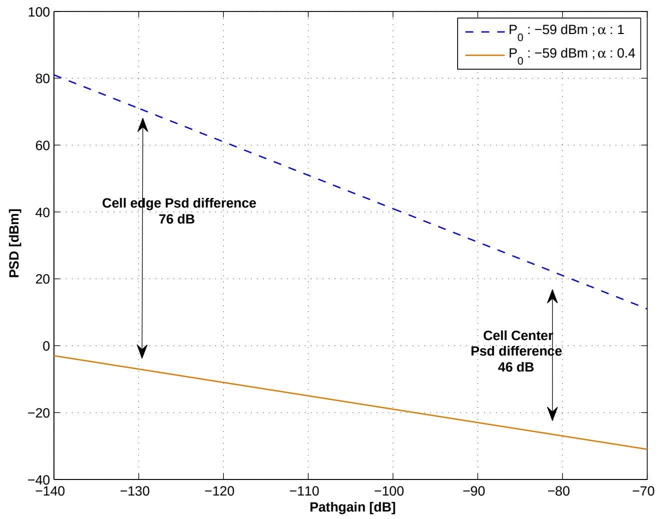

Figure 2.1: PSD compensation with Pathloss - A difference in Psd of 76 dBs can be obtained on cell edge users when comparing $\alpha = 1$ and $\alpha = 0,4$ while in the cell center the difference is 36 dB

The second case, $\alpha = 0.4$, shows the same tendency for the result but with a less spread distribution. Different slopes (the slope is α when the figure is seen in dBs) show that depending on the pathgain the compensation for pathloss is different. Around -80 dB of pathgain for example, the difference on PSD between the two α values is around 46 dBs while around -130 dB it is 76 dB. The previous is interpreted as the cell outage user (low PG) are more penalized according to the value α.

The case of $\alpha = 0$ represents no PC, since all users are targeted to transmit with the same power, while with $\alpha = 1$ is when they transmit with a power that intends to totally compensate for their pathgain, a case referred to as “full compensation”.

Values of α between 0 and 1 are cases that represent a compromise between the full compensation and no PC where only a fraction of the pathgain is compensated to the user. This, gives the name to the technique, Fractional Power Control.

According to the specifications α can only take the values [0 0.4 0.5 0.6 0.7 0.8 0.9 1] [(4)]. Noting that the zero value is included for the purpose of “turning off” the PC, while the following is 0.4. The fact that values between 0.4 and 0 are not included indicates that already int he specifications there are some practical cases that are not of interest.

To extend the analysis of effects of these two parameters, more than just the *psd* needs to be analyzed. The user i experienced SINR, expressed in Equation (2.5), is the first figure of interest.

$$s_i = \frac{r_{PSD}}{I + n} \qquad [-] \tag{2.5}$$

Where s_i denotes the SINR of user i, r_{PSD} is the received psd of user i at its serving BS. I is the interference density while n is the thermal noise density level both perceived at the BS serving user i. This and the following expressions are valid only for an instant on which none of the elements vary and when the densities are constant along all the transmission bandwidth.

The received power density, r_X can be simplified into 2.6, which is the transmitting psd over the transmission bandwidth multiplied by the total pathgain pg [2].

$$r_X = psd_i \cdot pg \qquad [mW/Hz] \tag{2.6}$$

Where psd_i is the power spectral density of user i and pg is the total pathgain from user i to its serving BS. If psd_i is known to be set according to FPC then the previous can be written as Equation (2.7), by substituting Equation (2.3) on (2.6).

$$r_X = p_0 \cdot pg^{(1-\alpha)} \qquad [mW/Hz] \tag{2.7}$$

Finally, replacing the received power spectral density on Equation (2.5), the SINR related to FPC is obtained:

$$s_i = \frac{p_0 \cdot pg^{(1-\alpha)}}{I + n} \qquad [-] \tag{2.8}$$

Figure 2.2, shows a Cumulative Distribution Function of the user experienced SINR in the system. Two examples of how the information is extracted from it are illustratory: for $P_0 = -65dBm$, a randomly picked user has a 50 % probability of experiencing a SINR of 5 dBs or less. On the same case, 10 % of the users of the obtained distribution experience less than 1 dB on SINR.

[2]The term pathgain is used here encapsulates the effect of the antenna pattern, distant dependent pathloss and shadowing, it is constant for the transmission bandwidth. See appendix A

Equation (2.8) is not directly proportional to p_0. Figure 2.2 shows that an increase of 5 dBs in P_0, for example, does not result in the same SINR increase. In fact since P_0 is equal to all users in the system, an increase of it will rise their Tx power and thus, the interference perceived by all BSs. In this case the difference results around 0.8 dBs in the median.

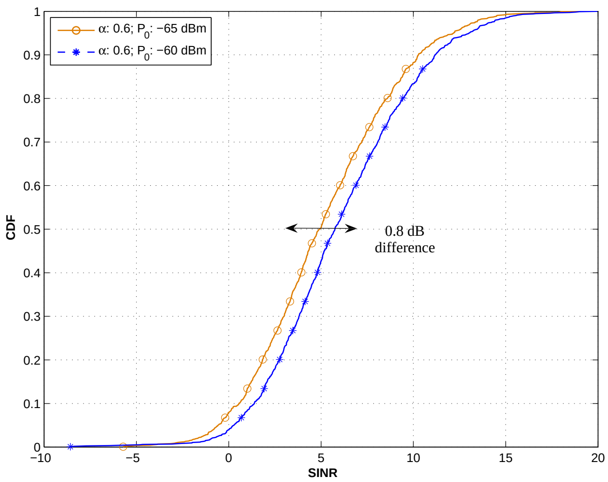

Figure 2.2: Effect of P_0 on SINR distribution - It graphically shifts the distribution in less amount than the psd

Similarly, a change of α affects each UE Tx power, making it higher for higher α values. Graphically, a "shift" similar to that caused by P_0 should be observed. But as the result shows in Figure 2.3, it affects the spreadness of the distribution because the more it gets close to the value 1, the SINR becomes more correlated to PG. In the contrast case - as it approximates to 0 - the correlation is lower.

From Equation (2.8) for $\alpha = 1$ (full compensation), all UEs are targeted to experience the same SINR by totally compensating for their pathgain in the Tx psd distribution. The term $p_0 \cdot pg^{(1-\alpha)}$ is equal to 1.

The distribution for the full compensation case is nearly 97 % around 4.8 - 5 dB of SINR. It is also noted how the operating P_0 values are quite different for both cases. In this case P_0 is set aiming to obtain the same interference levels. In this CDF it's clearly identified how the less spreadness caused by a high α, means less differentiation of user performance achieved with a sacrifice of the cell center user (those who experience high

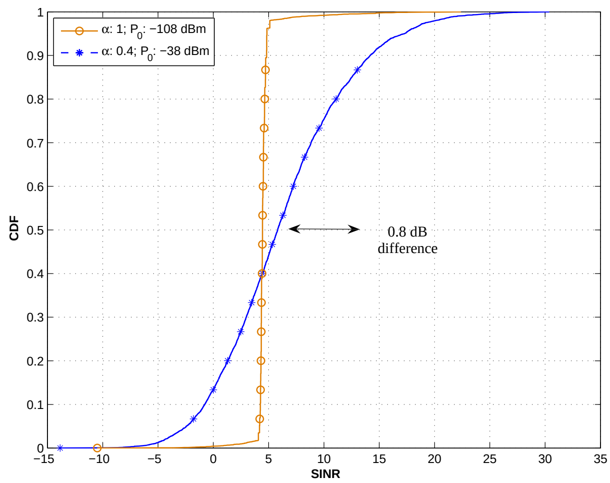

Figure 2.3: Effect of α on SINR distribution - α Spreads the curve, it determines how differentiated will the users be in terms of SINR

SINR with $\alpha = 0.4$) that improves the cell outage (experiencing low SINR).

In SINR terms, α is used to set the compromise between cell outage and cell center users while P_0 tunes the Tx psd, affecting equally all users.

Since the effects of the parameters on the psd and SINR distribution allow certain "tunability", it is possible to explore the performance of the system obtained for different combinations of them.

2.3 Fractional Power Control Performance

Each possible combination of α and P_0 define an operational point of FPC and a consequently performance. The objective is now to extract cases of interest out of all the available cases. The default assumptions are summarized in Appendix A.

2.3.1 Operating points

An appropriate approach to explore the different operating points is to fix α to later construct a curve for different P_0 values, since the possible values that the α parameter can take are limited.

Figure 2.4 shows the result of doing this, for the cell outage and cell throughput respectively. The relation in this figures represent how the the dependency of the cell and outage throughput with P_0 is for a given α.

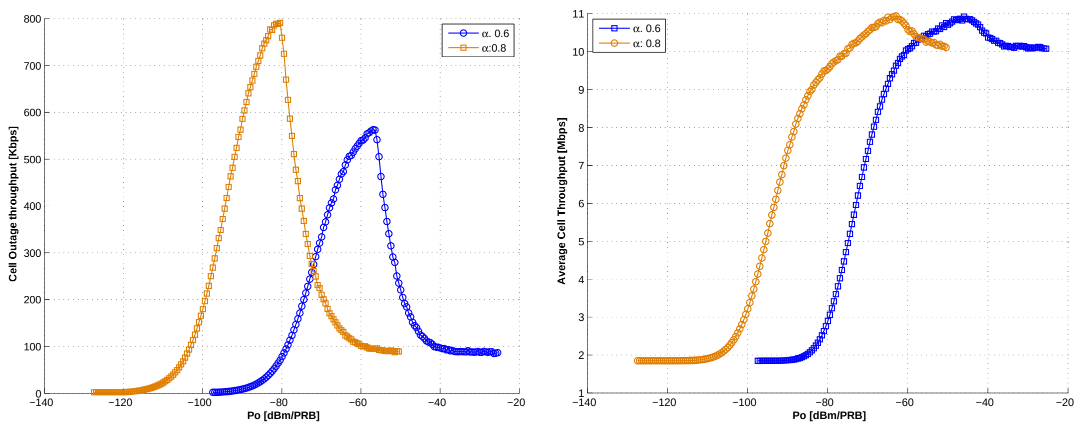

Figure 2.4: Outage (left) and Cell throughput (right) vs P_0 for $\alpha : 0.8$ and $\alpha : 0.6$ - The value P_0 that maximizes outage is identified here. It does not correspond to the peak cell throughput

Both α cases show an increase of cell and outage throughput up to a certain P_0, after which the outage shows a significant drop while the cell throughput still steadily increases. It is observed how the peak outage point does not correspond for cell and outage. After the peak outage points the cell throughput is still improving but this gain in only marginal.

The cell throughput vs P_0 is shifted for the two different α which indicates that the same levels are achieved with a different P_0. It not the case for the outage, however, where there is a shift and a lower throughput for $\alpha = 0.6$.

These two curves illustrated together show better the overall FPC performance. For example, for a set of α values all the operating points can be evaluated by simulating all the dynamic range of P_0 [3], Figure 2.5 show the performance bounds of FPC using this method.

As expected, Figure 2.5 shows that higher α favor more the outage while lower result in superior cell throughput. It is noted how the case of no PC drives a very low outage performance, a result that indicates that the interference levels are harming particularly this subset of UEs.

With all the peak outage cases are taken, a handful subset of outage optimal operating points can be defined, like it is summarized in Table (2.1).

[3]The dynamic P_0 range is bounded by the minimum value that makes at least one UE exceed the minimum power limit and the minimum value that makes all the UE exceed the maximum power limit

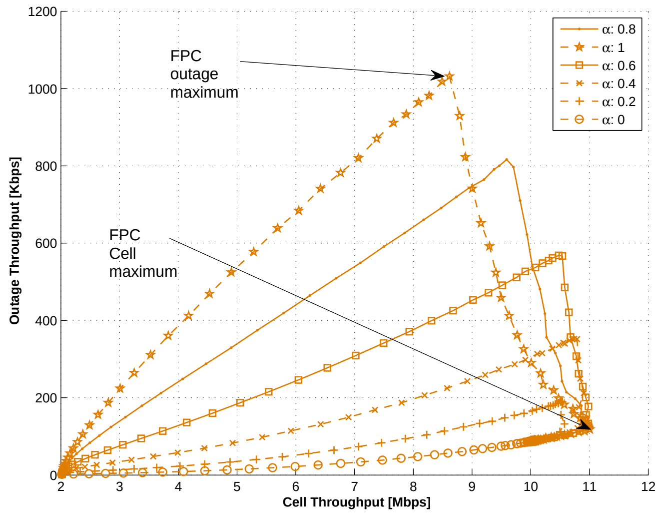

Figure 2.5: Outage Throughput vs Average Throughput for different values of alpha - The boundaries of this PC technique are illustrated, $\alpha : 0.6$ and $\alpha : 0.8$ are of particular interest

	Cell Outage [Kbps]	Cell Throughput [Mbps]
$\alpha : 1$	1012	8.6
$\alpha : 0.8$	806	9.58
$\alpha : 0.6$	565	10.54
$\alpha : 0.4$	362	10.79
$\alpha : 0.2$	189	10.54
$\alpha : 0$	123	10.08

Table 2.1: Maximum Cell and Outage Throughput values FPC - The chosen reference curves are $\alpha : 0.6$ and $\alpha : 0.8$ since they compromise both performances with higher values

The value $\alpha : 0.6$ has been chosen in some reference work [(9)] to be the optimum case (together with the value of P_0 that maximizes the outage throughput which differs slightly due to simulation assumptions), reason why it's also chosen for reference in this work. $\alpha : 0.8$ is also chosen as reference as it proves a good performance when compared to the $\alpha = 0.6$ case.

The peak of outage points for these two chosen cases are located at $P_0 : -57 dBm/PRB$ for $\alpha : 0.6$ and $P_0 : -81 dBm/Hz$ for $\alpha : 0.8$.

Choosing an "optimum" however, is a rather subjective task since this operating point is more related to the actual implementation of the system, where practical conditions will concretely define how the cell coverage should be managed. For this reason the kind of conclusion to be taken comparing these two reference shall give more importance to relative gains and conceptual implications rather than the absolute numbers.

The last two analyzed results depend on the outage definition. It is wise to check what the considerations that regard this are.

One of the default working assumptions is a 5 % outage. Any different value simply means that a different point of the user throughput cumulative distribution function is observed. The reason for choosing such value is inspired on the reference work. The impact of changing it is visualized in Figure 2.6.

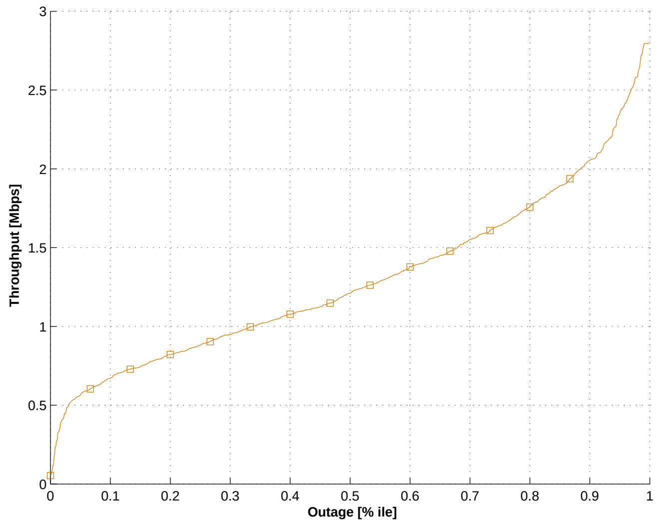

Figure 2.6: Throughput levels for varying outage, $\alpha : 0.6$**,** $P_0 : -57dBm$ - On the user throughput cdf, the outage is simply a point, and thus monotonically increases together with the outage % ile

The outage throughput is directly proportional to the outage value because a CDF is a monotonically increasing function. At a practical point of view it is interpreted as the higher the outage, the less the cell coverage, and as the cell coverage is considered lower, a better performance can be achieved because the users inside this area are most likely experiencing a high signal level.

Looking back to Figure (2.4) - which actually contains the chosen reference cases - it is noticed how the cell throughput shows the same range for both α cases, while the outage significantly drops (around 25% difference). This points that other figures should be analysed to understand the reason of such difference. The interference levels and the Tx P are part of the KPIs so a clear view of them is needed.

Figure 2.7, shows the Outage throughput vs the average IoT, revealing how the outage tolerates the interference levels. The case of $\alpha = 0.8$ provides a 25% higher outage throughput with 2.5 dB lower IoT compared to $\alpha = 0.6$. The similarity for IoT levels just above 15 dB indicate that over this IoT levels the outage tends to be highly penalized unlike the cell throughput.

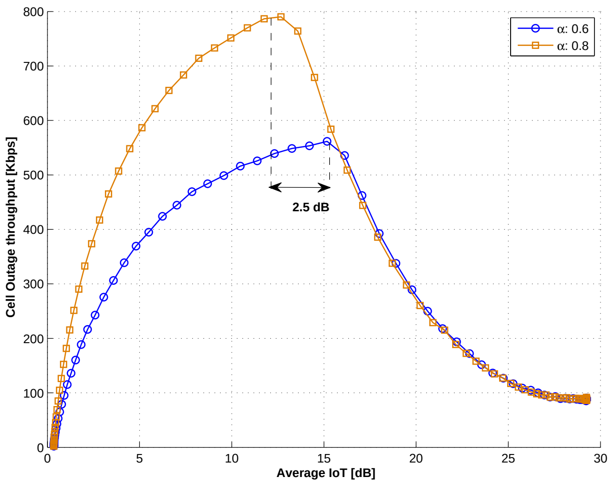

Figure 2.7: Cell Outage throughput vs average IoT for $\alpha = 0.6$ and $\alpha = 0.8$ - Different peaks are observed. higher IoT result in similar Outage performance

The average interference level is 2.5 dB different, it's deducted that a relation must be represent in the UE Tx P. Figure (2.8) shows that the case of $\alpha : 0.8$ results in a lower power distribution with a difference around 3 dB in median. This gives one reason for which the interference levels are different in the same magnitude. The biggest difference is in the Tx psd region where for the same probability up to 5 dB of difference are obtained whereas at high values they tend to be quite similar. It should also be noted how the amount of power limited UEs is the same for both cases. It is visualized as a sudden jump to a probability of 1 in $250mW = 23.97dBm$. while it's reminded how the outage for this result is the default 5%

To summarize, a low power distribution consequently results in low interference levels but at the same time drops the cell throughput. Also, there is a relationship between the number of power limited UEs and the outage: they are for these two cases the same percentile.

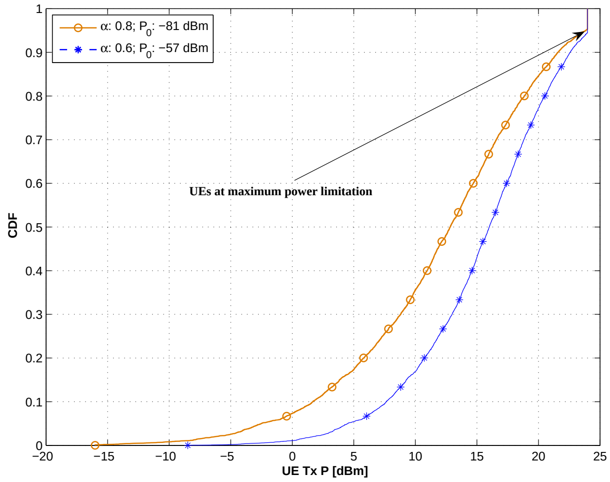

Figure 2.8: UE Transmitting power distribution for reference cases - The distribution for $\alpha : 0.8$ has generally lower power level

2.3.2 Analysis of optimum performance

Now the implications behind the main results are explored to explain the obtained results. Concretely the interference, has an important role which is yet to analyze.

The quantities $\Delta IoT/\Delta P_0$ and $\Delta I/\Delta P_0$ are partial differentiations of the average IoT and I (interference) with respect to P_0, which give a measure of the impact that P_0 has. This is a novel approach of analyzing the FPC standardized formula.

It is anticipated that both quantities are differentiated in dB (a ratio in linear) reason for which they are adimentional. For every point of P_0 the ΔI is evaluated as:

$$\Delta I = I[P_0 + \Delta] - I[P_0]$$

[dB]

Where $I[P_0]$ is the interference obtained for simulating with a certain P_0 and P_{0f}. Δ is set to 1 dB, but it's granularity is not of much importance as long as it is in the order of magnitude of the actual granularity of P_0 (which is 1 dB [(4)]).

It is known that their maximum theoretical value is 1 since the maximum total interference gain happens when all UE experience an equal increase in their transmitting psd (that means that no user experience a power limitation and is allow to power up with the increase of P_0). When this happens the average interference in the system raises exactly as much as the Tx power does, so the ratio should be equal to 1, the maximum.

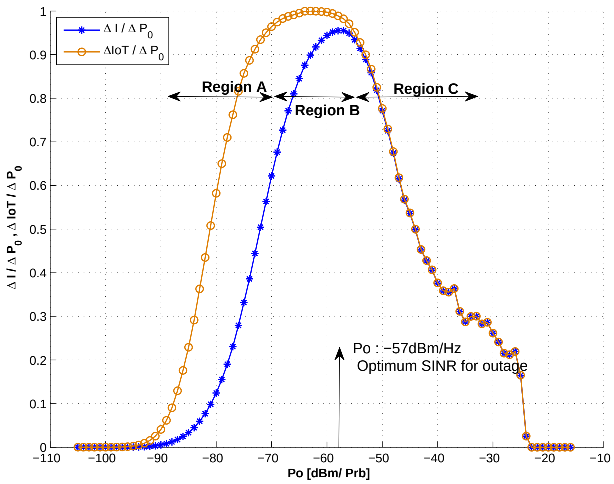

Figure 2.9: $\Delta I/\Delta P_0$ and $\Delta IoT/\Delta P_0$ - Derivative analysis of Interference

The effect of P_0 over the IoT is less than that of the interference because of the normalization to the thermal noise level (see Appendix B), specially true for lower P_0 values, but both figures provide with very similar information.

Three regions can be observed on 2.9, which illustrates the two quantities aforementioned:

- Region A: The minimum power limited region. Incrementing Po results in a growing increase of the interference, but the ratio is lesser than 1 since there are UEs below the minimum Tx P limit (the psd formula results in a psd lower than -16 dBm, forcing them to be at the minimum level)
- Region B: Non limited region. In this region there are not minimum nor maximum power limitations, so for the Interference, a linear increase is observed, meaning that the maximum increase of average interference is obtained
- Region C: Maximum power limited region. Similar to region A but with the maximum power limitation. At the end of this slope the fluctuations are caused because only few samples (UEs) remain under power limit [4].

[4]This is related to the calculations done with the tool. It is an usual and uncomfortable issue when calculating numeric differentiation, see appendix A

On Region A, the system operates with a considerable percentage, with minimum power limitations, which result effectively in both low cell and outage throughput. Reason for why it is not of interest when it comes to set the operating point. On Region B, the flatness indicates that the interference increases linearly with the increase of power, and so does the received psd of each UE to it's serving BS. But in the SINR the figure present is the IoT. The IoT slope, Figure (2.9), shows to still be increasing in the flat interference area of the interference (around $P_0 = -65dBm$ for example) The beginning (left part) of the flat region of $\frac{\Delta I}{\Delta P_0}$ is sustained to potential increase of SINR because the increase in IoT is lower than the increase of signal, this is known because $\frac{\Delta IoT}{\Delta P_0} < \frac{\Delta Rx}{\Delta P_0}$gining (left part) of the flat region of $\frac{\Delta I}{\Delta P_0}$ is sustained to potential increase of SINR because the increase in IoT is lower than the increase of signal, this is known because $\frac{\Delta IoT}{\Delta P_0} < \frac{\Delta Rx}{\Delta P_0}$

Region C indicates that those UEs which do not contribute to the interference are power limited, reason for why the ratio $\frac{\Delta I}{\Delta P_0}$ and $\frac{\Delta IoT}{\Delta P_0}$ drops. But it still increases, which means that these subset of power limited users perceive only an increase in the interference, reason that makes their performance drop.

Conceptually, this region B is the region to set the operational point since on it no UE suffer any penalization, while in practice it can be operated in Region C, where some users (the power limited) can be sacrificed to obtain a higher system performance. It should be noted that it is the case of the reference points.

The number of power limited UEs has already indicated to have an important impact on these results, now their amount will be studied by calculating the percentile of maximum and minimum Tx power limited users.

The complement of these quantities are shown in Figure 2.10 in two different curves (blue), it is immediately verified that is closely related to the interference slope. The complement of users with minimum power limitation "reacts" later than $\frac{\Delta I}{\Delta P_0}$ because for a given increase of P_0 UEs may reach the minimum limit level but the rise on the slope won't be seen until a further increase is made, and the contribution is actually done.

Its remarked that, nearly the same percentage of users experiencing maximum power limitations and outage is obtained, better seen in the psd distributions on Figure (2.8) where this is true for both chosen cases.

In fact, in Figure 2.11 the outage is defined at 0 % and the peak is observed at $P_0 : -63dBm$, which is the same point that shows the first UE with power limitations

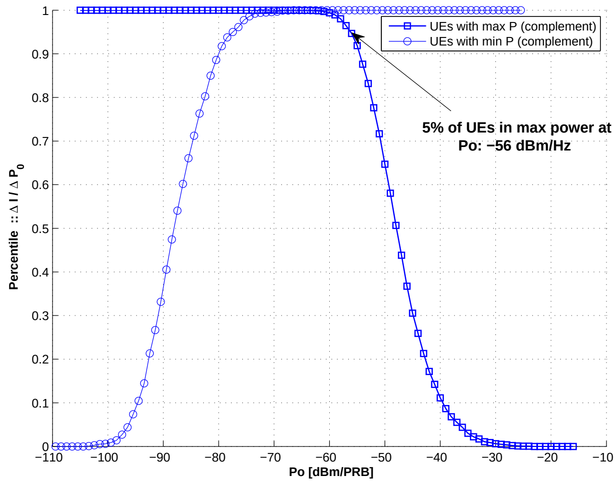

Figure 2.10: Power limitations and $\Delta I/\Delta P_0$ - The percentage of UEs limited by power is correlated with the interference derivative

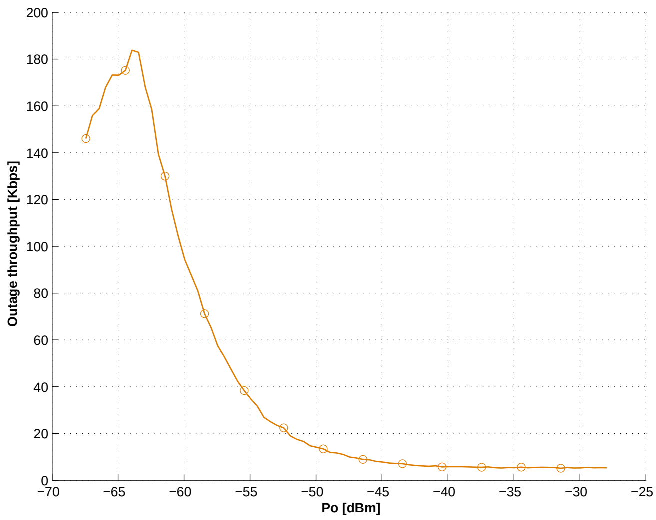

Figure 2.11: Outage throughput vs P_0 for an outage of 0 % - The peak of outage is observed when the first user reaches the maximum power limitation

on Figure 2.10. Meaning that the contribution to interference frops when 1 UE is limmited, when this happens the 0 % peak outage is found.

It is clear that the interference level is quite important to define the operational point, and the power limitations is what makes a user drop its performance if all users are powered up.

2.4 Conclusions

The standardized equation for FPC allows to set the user transmitting power according to the fraction of PG that the user has to compensate for. The parameters α and P_0 can be set in order to have an operating point on which cell performance and outage are accordingly compromised.

Two cases are extracted to provide with reference, representative enough to compare further PC techniques. The parameters, along with the data rates and IoT level compile the most important information of the performance. These are summarized in table (2.2)

P_o [dBm/PRB]	α	Cell Throughput [Mbps]	Outage [Kbps]	IoT [dB]
-57	0.6	10.55	565	15
-81	0.8	9.58	806	12.5

Table 2.2: Operating Points for FPC - The chosen reference points

The 5 % and the optimum case selection are rather subjective, these are based on resutls of previous work, but their purpose is to provide with relative gains/losses and are consequently valid. However when it was proven that the power limitations play an important role when defining the optimum outage no specific consideration of outage was done so the result is still correct for any value it can take. The ammount of users with power limitation and the outage optimum are very close to each other in these results, small differences may be attributed to the granularity of 1 dB of values of P_0

Simplicity is one of the key factors when considering the implementations, and FPC can be considered to provide have the lower boundaries since it is OLPC . And it also sets the starting point for further improvement. Only the Closed Loop corrections are at hand to achieve a superior performance.

The operating point $\alpha = 0.6; P_0 : -57dBm$ is now referred to as FPC case 1 and $\alpha = 0.6; P_0 : -57dBm$ as FPC case 2.

3

Interference Based Power Control

Now a PC technique is proposed with the purpose of improving the performance of FPC studied in the previous chapter. First the concept of interference based PC is formulated to later evaluate its performance and analyze the results.

3.1 Motivation

FPC is designed to allow a distribution of power that makes users who experience a low pathgain to the serving node obtain a consequently low SINR. Such distribution can be tuned to favor the cell outage or cell performance.

To differentiate the users in terms of psd, only a measure of the pathgain to the serving node is used. The assumption behind this is that users experiencing low pathgain to the serving BS reciprocally experience a high pathgain to others, and thus, they are the the ones that potentially generate the most interference. The assumption can be verified using information extracted form the model of the system.

Each user can be associated with two measures: the pathgain to the serving BS [1] (PG_S) and the total pathgain to other BSs (PG_I), which is the sum of each pathgain the user experiences to any BS except for the one that serves it.

Figure 3.1 illustrates PG_I vs PG_S for each UE. First observation is clear, there is a high correlation between the two pathgains. Second, for the same PG_S up to 20 dBs of difference on PG_I can be experienced by the users.

[1] The terms eNB, Node and BS are used indistinctively

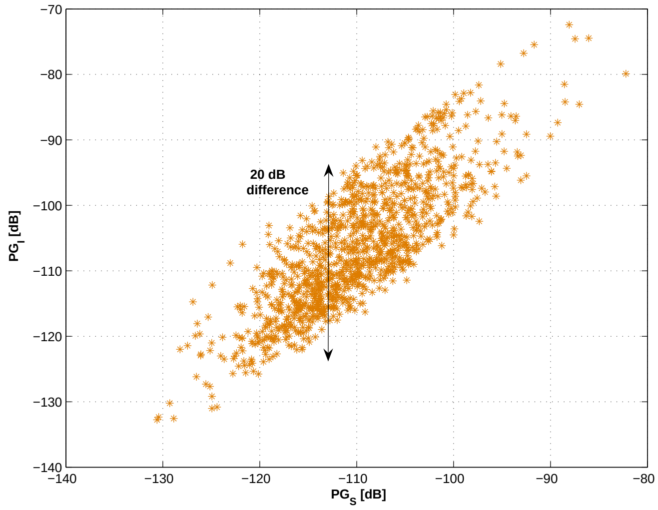

Figure 3.1: Pathgain to serving node vs sum of Pathgain to the rest of the BSs - For the same level of PG_S, a difference as high as 20 dBs is possible for PG_I

With FPC, the Tx power is set higher for low PG_S values. According to the first observation, a user experiencing higher PG_S is in average also experiencing a PG_I that has a comparable magnitude, the result is that the power is set to be higher to those UEs that have the most interference potential. Moreover, the consequence of the second observation is that for users who are set to transmit with the same power, up to a difference in the interference they cause is obtained.

These two cases result in a total higher interference level in the system and a high variation of the user generated interference, even for those who are set to transmit with the same power. Therefore, potential improvement could be achieved considering also the term PG_I to set the the Tx psd of the UE, penalizing those that have a high interference potential.

3.2 Interference Based Power Control

Instead of analyzing the interference received in a BS, attention is driven first to the total interference generated by a single UE. for a given user, Equation (3.1), represents the sum of the power received at each node in the system except for the serving, or the total interference it generates. This is valid only as an instantaneous measure. BW_i is the allocated Bandwidth to user i in the instant considered, and $PG_{i,j}$ is the pathgain from user i to BS j.

$$I_i = BW_i \cdot psd_i \cdot \sum_{j \neq s(i)} PG_{i,j} \qquad [mW] \tag{3.1}$$

The term $\sum_{j \neq s(i)} PG_{i,j}$ is the PG_I factor introduced in the previous section, and the node that serves user i is denoted by s(i).

3.2.1 Interference Limit

The first approach is to set an interference spectral density limit I_0 in the system so that all UEs generate at most this amount. The interference spectral density limit is modeled as Equation (3.2) for user i with a total interference generated I_{li}.

$$I_0 = \frac{I_{li}}{BW_i} \qquad [mW/Hz] \tag{3.2}$$

The psd_i can be derived from 3.1 and using the interference spectral density limit results in equation 3.3.

$$psd_i = \frac{I_0}{pg_I} \qquad [mW/Hz] \tag{3.3}$$

It should be clear that the interference spectral density limit I_0 is equal to all users in the system, while the interference limit I_{li} is not. Its difference is caused by the different Tx bandwidth among users. Nevertheless, a general assumption for the result of this work is a fixed bandwidth, so the results are expected to show also a constant interference level.

Equation (3.3) is taken to be the formula to set the transmitting psd instead of the FPC expression, and results can be obtained, where the interference spectral density I_0 is the only parameter to tune in the technique.

3.2.2 Performance with interference limit

The interference generated per UE is an easily evaluated result because it is expected to be constant. To extend the information of it, Figure 3.2 shows I_i vs UE Tx power for a simulation with $I_0 = -157dBm/Hz$. In this figure the distribution of the interference along the allocated power per user is visualized. Since the users have different interference potential PG_I, different Tx power is set so they are able to generate generate the same interference.

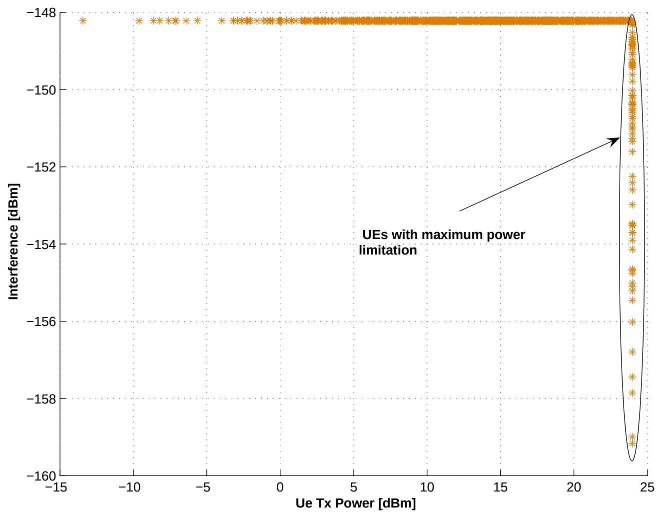

Figure 3.2: Transmitting power vs interference generated for interference limit - There is a subset of UEs that might not reach the interference level due to power limitations

Figure 3.2 shows that a subset of UEs are generating different interference than the limit, all gathered at the same Tx power. The reason is that the target psd of Equation (3.3) and the bandwidth (default is 6 PRBs) make a subset of UEs exceed the limitation which is around 24 dBs. But the limit is still valid, since this subset of UEs can only generate less interference. The Tx power distribution is scattered over around nearly all the dynamic power range, which is 40 dB.

The previous result was obtained for a single operating point. Now the focus is changed to find the impact of varying I_0. If Equation (3.3) is expressed in dBs, like in equation 3.4, it's seen how I_0 has the same form that P_0 has on the PSD of FPC, Equation (2.2). Their difference resides in that P_0 is expressed as total power on a PRB while I_0 is directly a power spectral density. However, this regards the implementation and can be let aside for now.

$$PSD_i = I_0 - PG_I \qquad [dBm/Hz] \tag{3.4}$$

It is possible then to analyze the outage and cell performance the same way as it was done for FPC: varying I_0 over a wide range to obtain a view of its bounds. The result is shown on Figure 3.3.

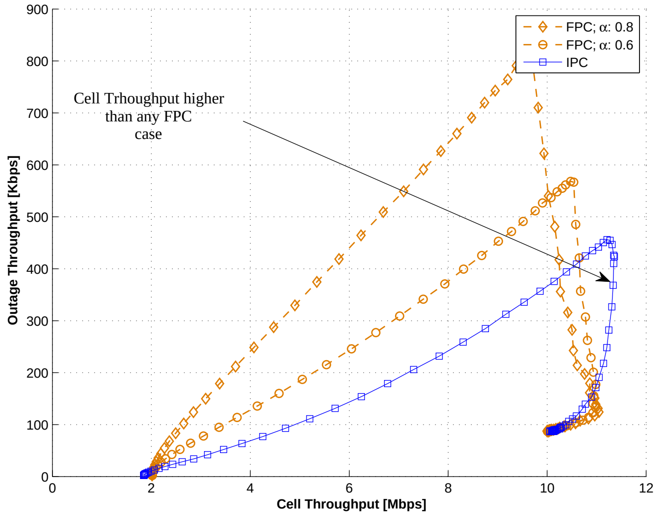

Figure 3.3: Outage Throughput vs Average Cell Throughput of the Interference limit compared to FPC - Hihger Cell thoroughput is obtained, yet the outage is penalized

Both cell and outage show a steady increase until the outage finds a peak at $I_0 : -157dBm/Hz$. Beyond this value, the outage drops considerably. An analogous result to the obtained for P_0 on FPC, verifying the similarity of these.

This peak of outage is an operating point The distributions of Tx power and SINR for it are shown in Figures 3.4 and 3.5 respectively.

The SINR cdf is spread over a range of 30 dBs, crossing the median at 5.2 dB. Compared to both FPC cases, the distribution is more spread. It is also observed how the outage is considerably penalized (higher probability for lower values, when compared to FPC). The gain obtained from having more probability on higher SINR values (for example, 20 % of UEs above 10 dB compared to 19 % of $\alpha = 0.6$ and 3 % of $\alpha = 0.8$

respectively) that effectively increases the average user SINR in the system is less noticeable in Figure 3.3, due to the SINR-Throughput mapping which has a logarithmic slope (see Appendix A).

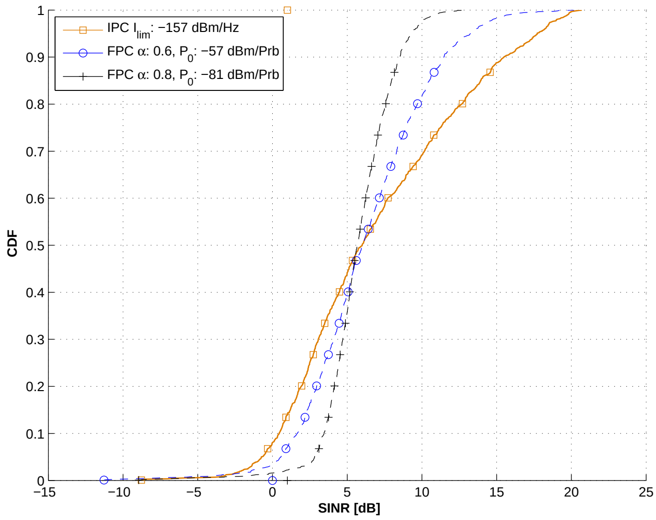

Figure 3.4: SINR cdf for IPC - The distribution concentrates more in the higher region

The UE Tx power distribution has more probability in the lower values compared to $FPC\alpha = 0.6$ while higher when compared to $FPC : \alpha = 0.8$. While it's remarked how all cases show very similar probability near the power limitation. In fact with the interference limit the peak outage case is also showing a 5 % of maximum power limited users.

The outage performance is dropped when compared to both cases of FPC while the cell throughput reaches higher values (up to 11.36 Mbps) compared to 10.98 Mbps achieved with FPC.

The average IoT in the system for the three cases are summarized in Table 3.1. IPC shows a 3 and 0.4 dB lower interference when compared to both $\alpha = 0.8$ and $\alpha = 0.6$ respectively, pointing that the interference received is indeed being reduced, under a desired level. Interestingly, the individual generated interference is set to be $-157 dBm/Hz$ which expressed in IoT is $12.25 dB$. This value is very close to the average received IoT obtained for this case.

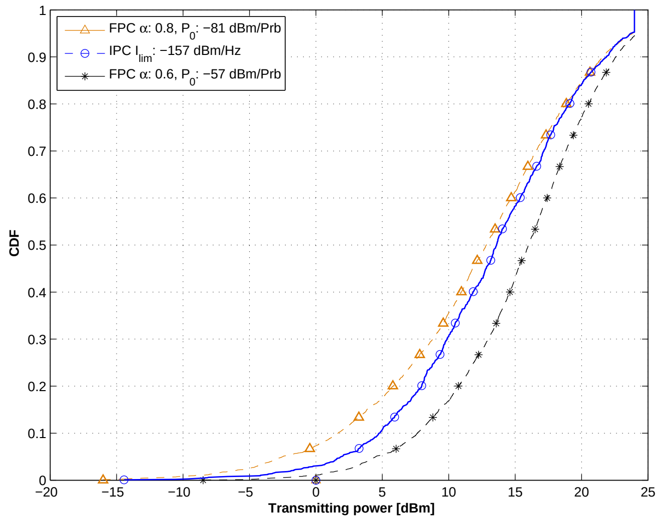

Figure 3.5: User transmitting power for IPC - The mean power is higher but the distribution concentrates in the lower region

Technique	Av IoT [dB]
FPC, $\alpha : 0.6, P_0 : -57dBm$	15
FPC, $\alpha : 0.8, P_0 : -81dBm$	12.5
interference limit, $I_l : -157dBm/Hz$	12.1

Table 3.1: Average IoT for optimum IPC and FPC cases

All the KPIs have been evaluated for the interference limit (Interference Based Power Control -IPC-) case. It can be concluded that this technique stabilizes or reduces the interference level in the system, but the penalization is too high for the outage and thus, the low marginal gain obtained for cell throughput indicates that this technique may be improved.

One reason for this drop of performance may be that information of PG_S is not used, a fact that is expected to have an impact on the system performance.

3.3 Generalized IPC

The purpose of including the term PG_S is to “tune” the outage performance, inspired on the way FPC works.

3.3.1 G-IPC concept

The previous technique (the interference limit), shows a reduction in the interference levels and a total improvement of the cell performance at the cost of outage. This cost proves to be too high. The term pg^{α} on the FPC technique, on its part, can improve the outage performance at the cost of cell throughput. A simple approach could be then to include this term in equation 3.3 aiming to obtain the same effect.

The factor PG_I can also be tuned using the same principle of the α parameter of FPC to obtain more operating possibilities. If the two proposed terms are combined, the resulting psd of a single user has the form of Equation (3.5)

$$psd_i = \frac{I_0}{{pg_I}^{\gamma} \cdot {pg_S}^{\beta}} \qquad [W/Hz] \tag{3.5}$$

Where:

- β: Is a parameter that affects the impact of PG_S on the Tx psd
- γ : Is a parameter that affects the impact of PG_I on the Tx psd

Using the same assumptions applied until now to analyze the KPIs it is possible to derive the SINR and I_i expressions that result when the power is set using this psd. First, substituting 3.5 in the user generated interference spectral density 3.1, results in equation 3.6.

$$I_i = \frac{I_0 \cdot pg_I{}^{\gamma}}{pg_S{}^{\beta}} \qquad [W/Hz] \tag{3.6}$$

Then substituting equation (3.6) on the SINR per UE expression (??), provides with the SINR per user with the G-IPC form 3.7.

$$S_i = \frac{I_0 \cdot pg_S{}^{1-\beta}}{pg_I{}^{\gamma} \cdot (I+N)} \qquad [-] \tag{3.7}$$

Given the equations of SINR, generated interference and transmitting psd, several special cases are identified, illustrated in Figure 3.6.

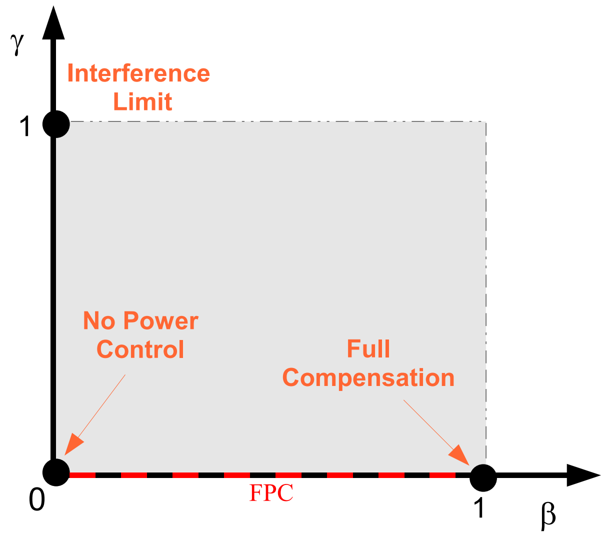

Figure 3.6: Cases of G-IPC - It is possible to set the power technique to obtain constant SINR, Power or Interference generated

The user generated interference in Expression 3.6, points that all UEs would generate the same interference spectral density to the system when $\gamma = 1$ and $\beta = 0$, that is, the case of interference limit shown in the previous section.

On the other hand, the transmitting psd expression 3.5 shows that the case of $\gamma = 0$ is equal to the FPC case, differing only in the definition of p_0 and I_0. They are only scaled by the bandwidth in Hz contained in one PRB, as explained before. If also

$\beta = 0$, the case of no power control is obtained, on which the transmitting psd is equal to all UEs. The full compensation case is located at $\beta = 1$. Equation (3.7) shows that in this case all UEs are targeted to experience the same SINR.

This technique has one more degree of freedom to set the Tx psd when compared to FPC, this obtained with the inclusion of PG_I. The results to be shown then, compile a few concrete combinations of I_0, β and γ to maintain the track of comparison that has been built around FPC.

3.3.2 Performance of G-IPC

The different performances obtained for all the possible operating points can be better understood if the effect of the newly introduced parameters is first studied.

3.3.2.1 Effect of The parameters on the distributions

Verifying the effect of the parameters γ and β on the psd distribution is rather simple, since equation 3.5 is dependent only on these, and of course the power limitations, if experienced.

Focus now is specifically on the psd distribution related to PG_S (Figure 3.7) separated in two cases, in one γ is fixed and β is let vary to see its effect (left) and the contrast case to see the effect of γ (right). The operational point is chosen for the value of I_0 that results in peak outage for each case.

To explain the result obtained, Equation (3.5) is analyzed, first written in dB.

$$PSD_i = I_0 - PG_S \cdot \beta - PG_I \cdot \gamma \quad [dBm/Hz] \tag{3.8}$$

The obtained result for the effect of β is expected as the the distribution is lineally dependent (if it is observed in dBs) to PG_S. This parameter is the slope, except for the PG_S values where the is power limitation.

Increasing γ (right) results in an increase of the spreadness of the curve. The reason is that for the same value of PG_S, there are many users experiencing different PG_I (this can also be seen in Figure 3.1). The correlation between the transmitting psd and PG_S is lower for high values of γ, while the case of $\gamma = 0$ corresponds to the maximum

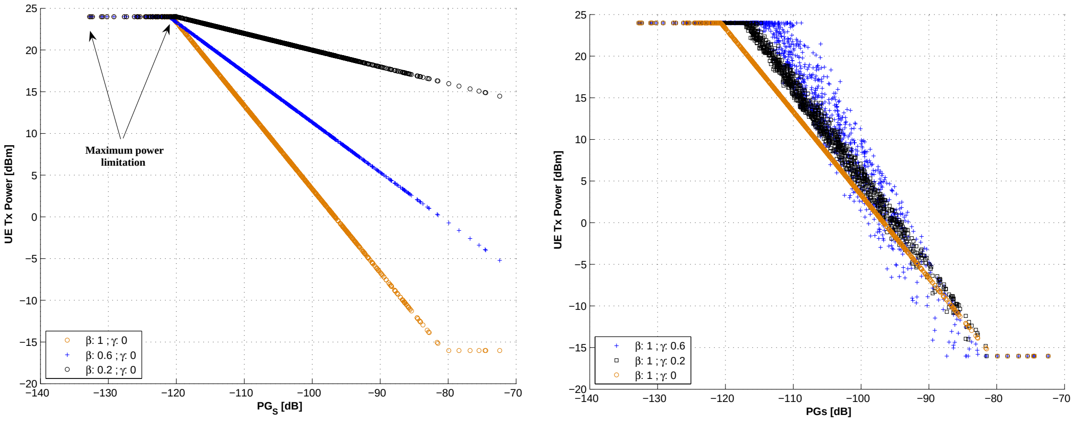

Figure 3.7: Effect of β (left) and γ (right) on Tx Power vs PG_S - β defines the slope of the distribution while γ defines the spreadness

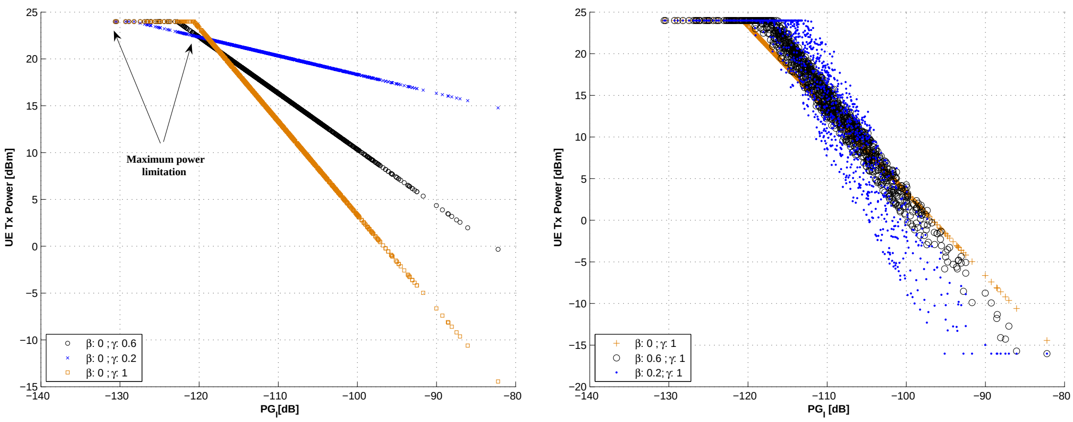

Figure 3.8: Effect of β (left) and γ (right) on Tx Power vs PG_I - γ defines the slope of the distribution while β defines the spreadness

correlation to it, where the spreadness is null. For this case the psd vs PG_S describe an inverse proportional line with β being the slope.

It is seen how on Figure 3.7 (right) the slope is negative and increases as β does, the same as in Figure 3.7 (left) with γ. 5 (3.8) does not justify such result if the distributions PG_S and PG_I are independent variables, which means that there is a high correlation between them. In fact this is a result consistent with the information of these distributions previously shown.

On the other hand, it is verified analytically and in the results, the effect of β on the Tx power vs PG_S distribution is reciprocous to that of γ on the same (Figure 3.8). And analogously, the effect of γ on the psd vs PG_I distribution is reciprocous to that of β on the psd vs PG_S distribution. There is an evident symmetry.

The Tx power distribution along PG_S and PG_I is translated in how the power is related to the user signal and the user generated interference. The slope Tx power vs PG_S indicates how the UEs are differentiated in signal, if it is more step, there is less differentiation. The full compensation (Figure 3.7 left, for $\beta = 1$) has a one to one relation. This can be tuned with β. The slope in the relation Tx power vs PG_I, analogously, indicates the differentiation of generated interference and the case of interference limit has a relation 1 to 1. This can be tuned with γ.

The spreadness of these relations also give a measure of the variance of the signal and generated interference per user. For example, $\beta = 0$ assures that for a given Tx power, only one level of interference is generated. Any value different than 0 indicates that there is a range of difference in the interference generated for user with the same Tx power. Analogous result is deducted for the user signal.

The FPC case (γ equal to zero) is subject to a higher differentiation in the interference generated per UE, partly explaining why the IoT levels are higher for it than for the interference limit case. Potential gain of IPC should be based on this tunning of the interference.

Finally, about the power limitation, the constant lines both at 23.9 and -16.9 dBm have information about the percentage of power limited UEs. An important remark arises in Figure 3.7 (left) when compared to Figure 3.8 (left): the amount of power limited UEs (remarked with arrows) remains the same for the effect of varying β on the distribution of transmitting PSD vs PG_S but is not the same when observing the effect of γ on Figure 3.8 (left).

3.3.2.2 KPI evaluation

The performance can be checked in terms of capacity. The approach is to simulate the system for combinations of γ and β varying from 0 to 1, and select the points of peak outage as it is known from the interference case that such would exist. So for every pair of γ, β a value of I_0 that maximizes the outage. The granularity for this parameters is also 0.1. It is known a priori what are the implications of having different pairs of γ and β with the previous analysis.

All these points are grouped and can be illustrated directly in the Outage vs Cell throughput indicator. Figure 3.9, shows the result for a subset of γ [0.4, 0.7 and 0.9] and all the simulated values of β. For $\gamma = [0.7, 0.9]$ the locations are similar, $\beta = 0$ starts in the bottom right extreme and increasing values move "inverse" clockwise until the upper left extreme.

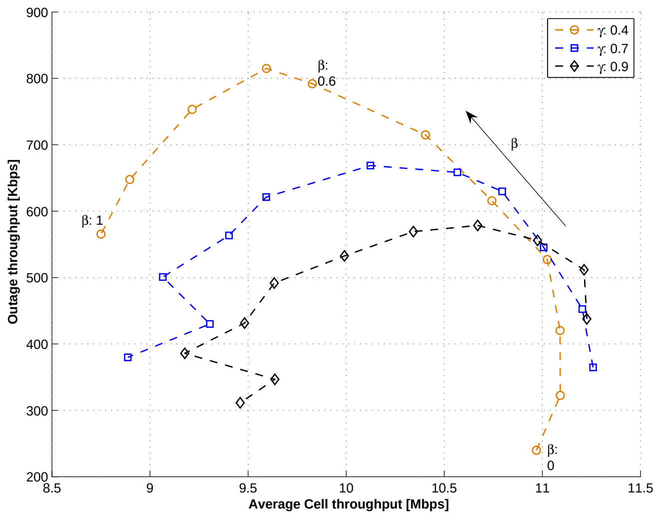

Figure 3.9: Peak outage points for $\gamma = 0.4, 0.7, 0.9$, β combinations on IPC - It is observed how each parameter tends to favor the cell throughput or cell outage distinctively

The peak outage locations show that indeed most of the gain in outage is obtained for higher β values while gain in average cell throughput performance is proportional to

γ. It should be noted that the bottom right edge means high cell, low outage throughput while the upper left means low cell, high outage.

Extreme cases have a simple intuitive explanation for their poor performance, based on the Tx psd. As it was demonstrated, high γ values result in a low transmitting psd of those UEs with a high interference potential. While high β or γ values attempt to lower the I_i and S_i variance, which was proved to be achieved by broadening the range of Tx power. If both are high , the total Tx psd distribution is extreme enough to drop the SINR for all user in the system generating low performances in both cell and outage. Similarly with low parameters (for example, no PC) the interference conditions are too high due to high Tx psd which tend to limit many UEs.

The message is simple then: high percentages of power limitations (both minimum or maximum) are to be avoided.

The points in Figure 3.9 are particular operational points, conformed by one β, one γ and the peak outage I_0. These peak outage points show very diverse performance.

Interestingly, the envelope of the constructed curves represents the case $\gamma + \beta = 1$. This case contains the best performance results in terms of throughput. Its analytical implications are worth a peek, in dB and applying the relation $\gamma + \beta = 1$ on 3.8 and group. The result is Equation (3.9).

$$S = I_0 - (1 - \beta) \cdot PG_S - (\gamma) \cdot PG_I - I - N \;\; [-]$$

$$\gamma + \beta = 1$$

$$S = I_0 - (1 - \beta) \cdot (\Delta PG) \;\; [-] \tag{3.9}$$

Where the difference $PG_S - PG_I$ is written as ΔPG. This way, the SINR can be expressed in terms of the user's difference of pathgain and only one parameter β or γ. This envelope offers a nice subset of boundary cases for G-IPC that can be directly compared with the reference FPC cases (Figure 3.10)

This is the main idea of one of the reference work [(7)], although the reasoning found on it starts from this assumption (expressing the SINR in terms of a difference of pathgain to serving node and non serving) to then derive the Tx psd form while the

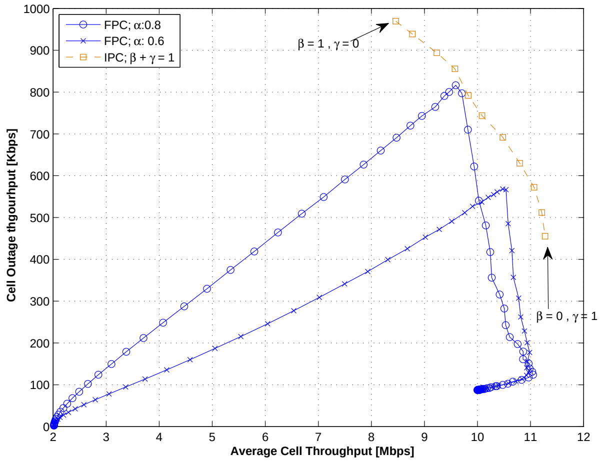

Figure 3.10: Peak outage points for $\beta + \gamma = 1$ compared to FPC - Only a subset of these offer a gain over the FPC cases

initial idea in this work has been of setting a user generated interference limit and then tune it.

Equation (3.9) helps interpret the technique. The UEs in the system will be differentiated in SINR according to the difference of experienced pathgain.

This envelope defines a line of operating points that is superior to any FPC case. This can be attributed to the similarity of the distributions of PG_S and PG_I, because the difference ΔPG is under certain bounds for all the UE's. However in the reference work it is not analyzed as an optimum case, and as it will be seen next section, this results depends of the user distribution.

To complete the comparison with the reference cases and and at the same time synthesis the results of G-IPC, out of all the combinations available, two particular cases are chosen: $[\beta : 0.7,\ \gamma : 0.3]$ and $[\beta : 0.5\ \gamma : 0.5]$, based on their performance in terms of capacity. It is possible then to extend the performance for a wide range of I_0, like shown in Figure 3.11. The operating points are quite similar to the reference cases of FPC. The gain in outage is mostly marginal.

The gain obtained with G-IPC over FPC is achieved with lower IoT levels, in the range of 3 - 3.5 dBs (Figure 3.12. It's noted again how for the upper range of IoT

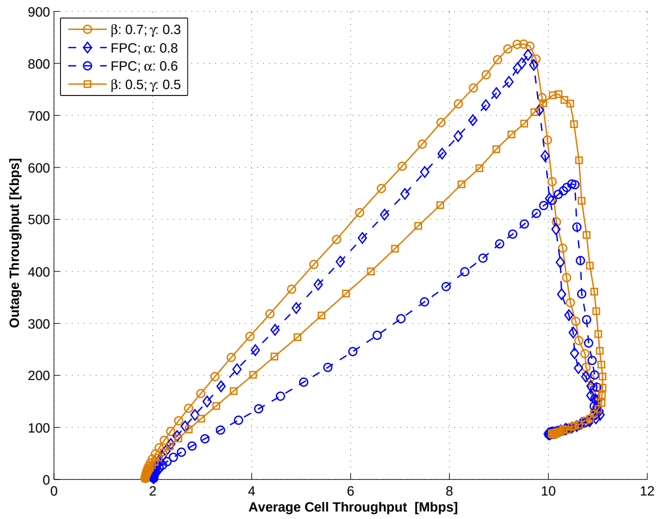

Figure 3.11: Outage vs Average cell throughput for chosen cases of GIPC - Very similar operational points are obtained

the outage tends to be similar for all cases because the system is operating with power limitations that affect the outage systematically the same.

The lower interference levels do not translate in a difference of the same range for the power distribution. Observed in Figure 3.14, specifically in the cases of FPC: $\alpha : 0,8$ with $\beta : 0.7$, $\gamma : 0.3$, the difference in median is around 2 dBs while the extremes of the distributions are very close, with a difference of less than 1 dB. In fact, the distributions are close enough to abstract one idea: there is a “power budget” that slightly changes between both cases, while the big difference resides in how this budget is distributed to users.

The SINR distributions on their part (Figure 3.13) show a very similar behavior, specially around the median where they all cross near 6 dB. In contrast to the interference limit case, this mechanism does not show a higher probability for the superior SINR values, but again, the effect is less noticeable when the throughput is observed, due to the Shannon capacity mapping.

The maximum power limited users and the maximum X % ile outage has been implicitly showing a relationship since the previous chapter. Finding its reason helps understand the performance of the technique.

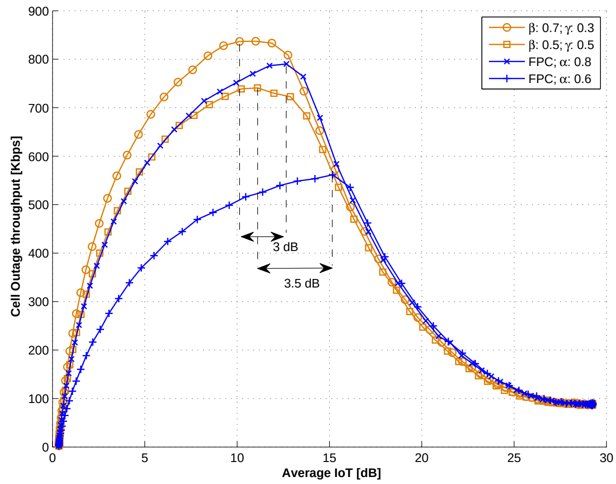

Figure 3.12: O vs IoT for GIPC chosen cases - Up to a difference of 3 dBs in IoT is observed for the outage peak points

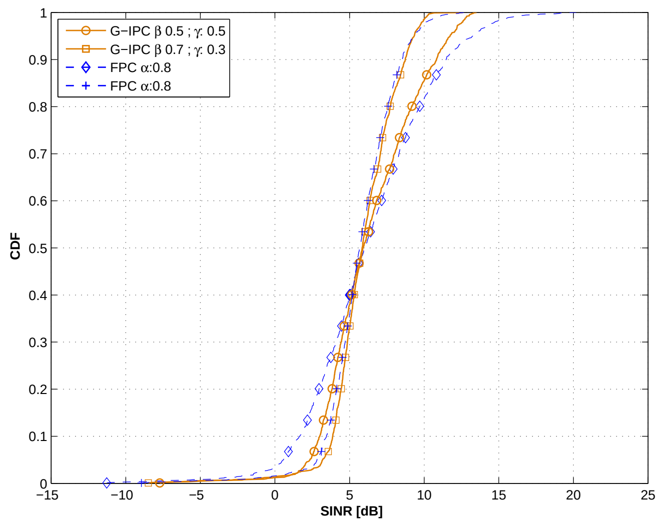

Figure 3.13: SINR for GIPC chosen cases - Very similar SINR distributions are obtained when compared to FPC. The most important difference resides in the extreme values of SINR

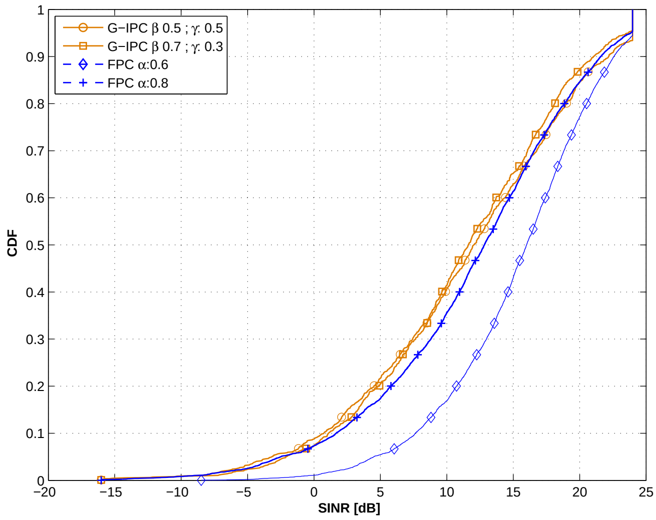

Figure 3.14: UE Tx for chose cases - The power distributions are consistently lower. Very close to FPC with $\alpha = 0.8$

3.3.3 The optimum X% ile

A particular case of equation equation 3.5, where $\beta = 0$ is tested now (FPC case) to see the relation between the optimum outage point and the power limited users.

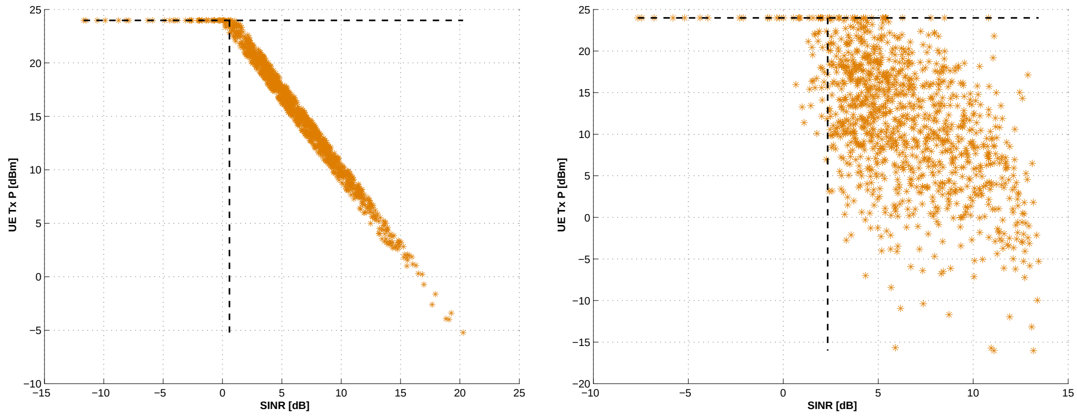

Figure 3.15: UE Tx power vs SINR distribution for FPC and IPC - In FPC the peak outage point happens when the user defining the outage is experiencing Max power limitation

Equations (3.5) and (3.7) show that the Tx psd is inversely proportional to the pathgain to the serving node while the psd is proportional to it (β cannot take values above 1). Then, if the Tx power is illustrated vs the SINR (Figure 3.15) for all the users in the system, a monotone curve is obtained. The power limitations are once again seen, remarked with the horizontal line. The vertical lines emphasizes the outage SINR (the UE that represents the 5 % of the cdf of the SINR).

This result verifies that for $\beta = 0$ (FPC), the UEs experiencing the worst performance are the ones transmitting with the most power. This linear dependence (in dB) between experienced SINR and Tx power that guarantees that any increase of I_0 would reflect on a power up of this curve (shift up) and the users will experience the power limitation in order, from the one with the worst SINR performance up to the best.

It is concluded that in this case the optimum outage for a X % point is found to be the minimum I_0 that makes the same X % outage to transmit with maximum power, since further increase will only deteriorate its performance (no increase in signal but increase in interference).

The correlation is lost, however, for G-IPC when γ has non zero values, this is because both SINR and PSD distributions now depend on PG_I. An example is illustrated in Figure 3.15, for the case $\beta = 0.5$, $\gamma = 0.5$, noting that some maximum power limited UEs are experiencing a superior SINR that that of the outage

Even thought this is a case of $\gamma = 0.5$, where the correlation is lost. It's noticed how the outage (the points to the left of the vertical line) still transmit with high power (above 10 dB) while some UE that experience power limitation which have a performance better than the outage user, are a low percentage.

This helps conclude that finding an optimum case for a given X % outage is not a trivial task because it depends of the configuration of users in the system, which in practice vary during time.

3.4 Conclusions

It has been shown that the improvement of the system performance is achieved by reducing the interference levels. At the same time this is reduced by distributing the power considering the interference potential of each UE. Compared to FPC case 2, the power levels are very similar, while the performance is very similar. This could be thought as if the power is budget which the system has and needs to distribute to cause the less interference possible.

The maximum gain is in outage, up to 28%, keeping the same average throughput. While the cases that result in high SINR do not refflect their gain so much in throughput due to the SINR-Throughput mapping.

One observation regards the optimum points. These are selected rather subjectively. If the interest is, for example, to provide the average user of the system with a total higher data rate relaxing the cell coverage demands. Then the interference limit case ($\beta : 0$ and $\gamma : 1$) would result rather attractive.

It's concluded then that this technique allows for more degree of freedom when selecting an operating point. In fact, FPC is one particular case of this technique. The property of "controlling" the interference generated might be of interest for other RRM functionalities in LTE UL, so even if it represent loss in outage under this scenario, cannot be ignored.

If the interest is to optimize the outage, FPC has an important correlation between the UE Tx P and the experienced SINR. The optimum X % outage can be found simply by forcing the corresponding X % outage to transmitt with maximum power. The optimum I_0 on G-IPC is found when the user that represents the 5 %, a fact that has a practical advantage. When $\gamma \neq 0$, however, the relation is lost.

As it was shown in the previous chapter, summarizing the selected operating points permits the direct comparison with the starting scenario of FC. Table 3.2 shows such compilation of results, where the gains over both cell and outage are appreciated along with the difference of IoT for the selected operating points.

Reference	I_0	**Beta Gamma**	**Cell [Mbps]**	**Gain over FPC [%]**	**Outage** [Kbps]	**Gain over FPC [%]**	**Av IoT [dB]**	**Diff FPC [dB]**
FPC_1	-157 dBm/Hz	0.7;0.3	10.44	(-1)	722	28	13.67	1.3
FPC_2	-156 dBm/Hz	0.5;0.5	9.63	1	843	5	11.91	3.09

Table 3.2: Summary of reference operating points

The analysis made until now serves as inspiration for the following technique. Specially the abstraction of the "power budget". The two reference cases are now written as GIPC case 1 ($\beta = 0.7\gamma = 0.3$) and GIPC case 2 ($\beta = 0.5\gamma = 0.5$).

4

Cell Interference Based Power Control

4.1 Motivation

The user experienced throughput is a function of the allocated bandwidth and the BW efficiency experienced in the transmission. While this depends on the selected, which in EUTRAN LTE UL, it is known to be selected according to the measure of average SNR .

Figure 4.1 shows a fit of the throughput obtained for different MCS orders that are selected according to the mentioned SNR. The curve fit is based on the Shannon Capacity expression [(13)] (more details on Appendix A), and provides a direct relation between the UE experienced throughput and SNR.

If A and B represent the experienced throughput of two users in the system at a given instant, it is seen how the same increase in SNR results in different throughput increase for both. In fact, the gain of throughput is lower as the experienced SNR increases. If one of this two users is to be given power for the next instant exclusively, the best candidate in terms of gain of throughput is the user A.

The previous power control techniques are designed to set the user Tx psd based on its interference PG_I and signal PG_S . The best performance cases were achieved by targeting the UEs with good trade off of signal and generated interference to experience a higher SINR.

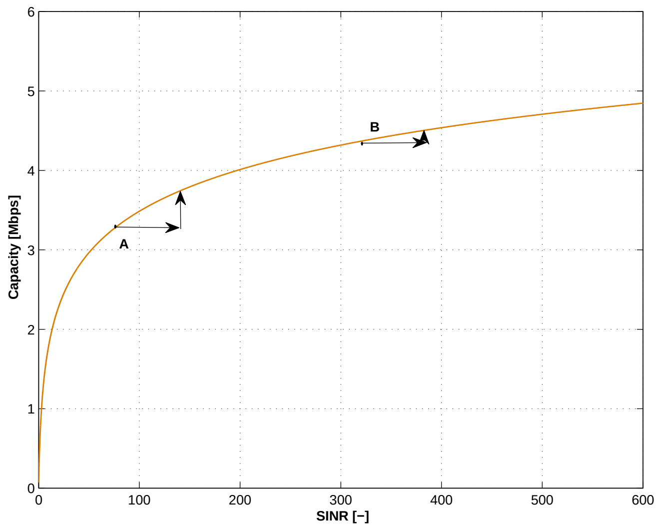

Figure 4.1: Capacity Shannon mapping for SINR for LTEl - For the same increase in SINR, point A results in more throughput gain than B due to the non-linearity of the Shannon capacity mapping

On Figure 4.1 for example, user B may represent a better trade off between signal and generated interference than user A, but not necessarily a better trade off between gain in throughput and generated interference.
In this chapter a PC technique designed to set the power according to a measure throughput which is what ultimately matters.

4.2 Design of the Cell Interference Based Power Control

A novel PC technique for the system is now proposed. First the concept is studied to evaluate after the results.

4.2.1 Concept C-IPC

Let it be considered the situation for which at a given instant an UE that was transmitting with a certain psd is powered up by Δpsd. An increase in Tx psd exclusively for this UE in the system. As a consequence of this, the user would experience an according increase in throughput ΔT and an increase in the generated interference ΔI. The quantity ΔT can be interpreted as a "gain", both for the system (UL throughput of the cell) and the user, while ΔI can be interpreted as the "cost" to the system. In the system point of view then, these are understood as the gain and the cost obtained from allowing the UE to increase its Tx psd by Δpsd.

If there are many UEs in a system and there is only one unit of power that can be assigned, the best candidate according to this criteria is the one who is attributed with the best trade off between ΔT and ΔI. A PC technique can be designed to use this this simple, yet key decision. In the other part, the fact that the information of the gain and cost is known a priori, implies that there is information about the generated interference per user and the experienced SINR.

The information about the interference generated can be extracted from the total pathloss to non the serving BS (PG_I) of the user , as in the previous chapter. However, the information about the experienced SINR requires the knowledge of the pathloss and interference received by the serving BS. The first term is PG_S, already in the standardized PC formula and can be taken for granted. Nevertheless, The interference in the cell would require either a measure or an estimation.

For the technique described here, an estimator which considers the average level of received interference is proposed. To do this, previous result are used as inspiration.

FPC and G-IPC, have shown that the range for the optimum IoT levels around 12-15 dBs. When the outage throughput is related to the cell IoT (Figure 3.12) for example, it is observed that the peak outage operating points are achieved with lower IoT levels, maintaining a comparable cell throughput. For G-IPC with $\gamma = 1$ and $\beta = 0$ which corresponds to the IPC case, the result of the interference generated per UE (Figure 3.1) has shown to be quite close to the average interference perceived per BS. The intention is then to relate the interference generated per UE to the received by the BS. It should be realized that the fact that the PC itself can have an impact of the interference generated would result of advantage.

On a cell basis, the total generated and received system interference, I_{Tg} and I_{Tr} respectively, can be calculated taking the contribution of each BS. Equations (4.1) and (4.2), express this, where I_{Gj} and I_{Rj} are the generated [1] and received interference of

[1]The generated interference of a cell is the sum of the individual interference caused by the users whom it is serving

BS j. N_{BS} is the number of BS in the system.

$$I_{Tg} = \sum_{j=1}^{N_{BS}} I_{Gj} \qquad [mW] \tag{4.1}$$

$$I_{Tr} = \sum_{j=1}^{N_{BS}} I_{Rj} \qquad [mW] \tag{4.2}$$

Equations (4.1) and (4.2), are known to be equal if no external sources of interference are considered:

$$I_{Tr} = I_{Tg} \qquad [mW] \tag{4.3}$$

If each cell sets a total generated interference I_{lev} constant and equal in the system, so that equation 4.1 can be written as:

$$I_{Tg} = \sum_{j=1}^{N_{BS}} I_{lev} = N_{BS} \cdot I_{lev} \qquad [mW]$$

And then substituting it in Equation (4.3) and solve for I_{lev} results in:

$$\sum_{j=1}^{N_{BS}} I_{Rj} = N_{BS} \cdot I_{lev} \qquad [mW]$$

$$N_{BS}^{-1} \cdot \sum_{j=1}^{N_{BS}} I_{Rj} = I_{lev} \qquad [mW]$$

Where the left term is an arithmetic mean. It can be concluded that if each cell generates a constant level of interference I_{lev}, in average, the received interference should be the same value. Equation (4.4).

$$E[I_{Rj}] = I_{lev} \qquad [mW] \tag{4.4}$$

This is convenient to estimate the received interference per BS and derive the gain (ΔT) for each user. If the PC technique is set to make all the BS generate the same amount of interference (I_{lev}) then, it can be used as an average estimator of the received interference. The user experienced SINR can be calculated as in Equation (2.8). If it is evaluated at a given instant with the potential increase of Tx psd Δpsd (if defined in dB it would result the same), it is possible to obtain the throughput that the UE would experience and if subtracting it from the current, ΔT. Noting that a mapping of throughput-SINR like shown in Figure 4.1 is required and the initial Tx psd of the UE is also needed at the BS. It is also required that the cell reaches the interference level I_{lev}. For the technique proposed here this will be conceived as an "interference budget" of the cell, which has to be managed in the most profitable way, allowing iteratively one UE (the best candidate) to increase its Tx by one step (in dB) until the target interference is met.

These conditions, a target convergence interference, a known starting Tx psd distribution and the throughput mapping are the fundamental elements to design a PC technique that is based on a gain/cost criteria.

The unacuracy of the estimator is evaluated empirically in the results, while the measurements and calculations and some assumptions needed are discussed in the implementation issues section.cy of the estimator is evaluated empirically in the results, while the measurements and calculations and some assumptions needed are discussed in the implementation issues section.

4.2.2 Description of the algorithm

The calculations done for Equations (4.1) and 4.2 consider the contribution of BSs individually, and it is a task of each to achieve the target interference level. This means that the algorithm is executed on a cell basis.

There are several requirements to design the algorithm in terms of measurements, estimations and assumptions.

First, there must be tools to estimate the signal and interference generated per UE. The pathloss to the serving BS PG_S and total pathloss to the non the serving BSs PG_I used in the previous chapter serve to this purpose adequately.

Second, the technique should allow certain adaptability. The quantity I_{lev}, for example, may be set arbitrarily since the impact of the interference level in the system is of interest. On the other hand, the resulting Tx psd distribution may be subject to constrains, such as minimum allowed psd or minimum experienced SINR.

Third, a criteria to distribute the steps of power is needed. To assess this, a figure that measures quantitatively the gain and cost trade (a metric) is defined as an input parameter of the algorithm.

The technique is defined to set the UE Tx psd so the power control functionality in the LA is maintained. The analysis of the previous section, nevertheless, is still valid. Following is the algorithm:

1. **Initial condition:** All UEs within the cell are transmitting with a known power, allowing to estimate their experienced throughput and the current cell generated interference. **Alternatively**: Use the information of PG_S and I_{lev} to set the Tx psd of all UEs to a required minimum SINR
2. Metrics are constructed based on the information of each user (PG_S and PG_I) and the current generated interference
3. If all metrics are null, end
4. The UE with the highest metric is selected to increase its power in one step
5. If the selected UE would reach its power limitation its metric is null and go back to (3)
6. If the total cell interference would be exceeded when the selected UE increases its power by one step, is metric is null and go back to (3)
7. A signal is sent to the selected UE to increase its power by one step, go back to (2)

The metrics are assumed to be non negative quantities, while the zero value means that the UE associated to it is not a candidate to power up. The flow diagram representation of the algorithm is shown in Figure 4.2.

It is seen that the criteria used to distribute the power among UEs would result in a different priorization for them. If their initial Tx psd is low, for example, then the steps are assigned iteratively to the best candidate for each state until the target interference level is achieved. Since the users are obviously differentiated at this point, it is recognized that the metric the critical parameter that ultimately affects the performance of the algorithm. This suggest that a more detailed look should be paid to them.

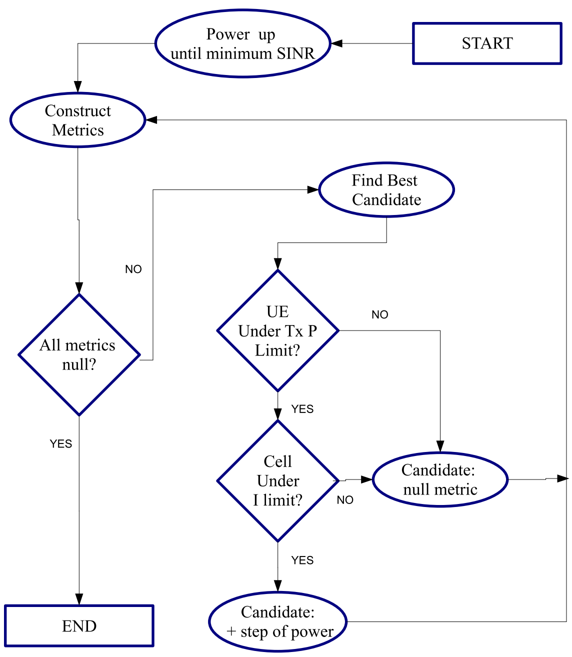

Figure 4.2: G-IPC flow diagram - Represents the mechanism for one cell

4.2.3 Metrics

There are infinite ways to define the metric. But of course, not all would match the goal of improving the performance obtained with G-IPC. For this reason, two metrics have been chosen to illustrate two different orientations they may have: cell oriented and user oriented.

The diagram illustrated in Figure 4.2 shows that the metric only affects how the candidates are selected, making the importance of it to be how they are defined relatively to each user.

For example, in the following hypothetical metric per user:

$$M_{hyp} = A + B \cdot PG_S$$

Different values of A would not result in any change, since the effect will be the same on each user. On the other hand, only three different results would be obtained for the possible values of B, one if it is greater than zero, one if it is lesser and one if it is zero. On this last case the metric is identical to each user in the cell and the algorithm is designed to randomly choose one as the best candidate since the information is insufficient.

One of the two analyzed metrics is now introduced. The term "gain over cost" per UE is explicitly a quantity that can be used. Equation 4.5 shows this ratio to be a metric per UE.

$$M_1 = \frac{\Delta T}{\Delta I_G} \cdot \frac{I_C}{T_C} \tag{4.5}$$

The term T_C is the current cell throughput and the term I_C is the current interference generated by the cell.

ΔT is the increment of throughput of the user for the step of increased psd, it can be calculated from the throughput mapping of SINR:

$$\Delta T = T[\tilde{S}(psd_0 + \Delta psd)] - T[\tilde{S}(psd_0)] \quad [bps]$$

	ΔT	ΔI	M 1	M 2
UE 1	0.5	1	0.5	**4.5**
UE 2	3	2	**1.5**	4

Table 4.1: Example of different criteria using metrics

Where T is the fitted shannon throughput mapping and $\tilde{S}$ is the estimation of the UE SINR based on the information of PG_S, the Tx psd and the interference target I_{lev}. On the other hand ΔI is estimated directly if the Tx psd and PG_I are known.

It is very important to realize that the last calculation is made assuming an interference level I_{lev} even though the cell may not be experiencing such level. It is of vital importance that the algorithm converges to this value, so that the estimations are done appropriately. The decision is done estimating a future interference level.

M_1 simply defines a ratio of increment of throughput over increment of generated interference, per UE. Those who would be given the most priority at a given iteration are the ones that represent the higher individual ratio. It should be noted that the normalization made by including the cell throughput and current cell interference affects equally all UEs and has no impact on the resulting distribution, however, it makes the metric a dimensional and fits its range of possible values.

Conceptually the criteria implied by M_1 tends to optimize the performance in the user point of view, because at each iteration the best candidate is selected without considering the actual increase of interference and throughput in the cell. So, another metric could also use a cell criteria. On Equation (4.6), the ratio compared is the gain in throughput of the cell over the increment of interference generated by it, considering the current state.

$$M_2 = \frac{\Delta T + T_C}{\Delta I_G + I_C} \cdot \frac{I_C}{T_C} \tag{4.6}$$

A simple example shown in Table 4.1 helps verify how these two metrics would result in a different priority for two UEs. The example considers $T_C = 13$ and $I_C = 2$.

The difference is that M_1 does not take into account the actual level of interference generated by the cell which in M_2 weights more. In the example, UE_2 would perceive more gain than cost but its contribution to the interference is higher tan that of UE_1, causing the second metric to be lower. The two metrics are then considered to be user-oriented and cell-oriented for the optimum performance. The dimensions and the normalization is neglected for simplicity, nevertheless, the relative result is the same.

In conclusion, the metrics define the criteria used in the technique. But just the relative priorization may not be sufficient to guarantee a minimum performance in the system, reason for why the minimum SINR parameter is needed.

4.2.4 Minimum SINR power distribution

For the algorithm described, steps of power are given to the selected candidate. This step of power is also a parameter that would affect the convergence of the algorithm depending of it granularity. For example, if the target I_{lev} is translated into an IoT target of 3 dB, a step of 2dB for the Tx psd may make it impossible to reach it depending on the initial power distribution.

The initial power distribution then affects the way the algorithm would converge. If it is generally low so that the initial interference generated by the cell is below the target, then the step can be set to +1 dB, which is the minimum values that the close loop term can take [(4)], and the convergence should be achieved when the generated interference limit is reached.

If the initial power distribution is high, it could be desirable to set a negative step, and construct one more metric per UE to find a best candidate to have power subtracted until it experiences a minimum SINR. This is a nice way of controlling the lower UE performance, or better understood, the outage performance.

To simplify, the initial power distribution will be assumed to be the minimum Tx psd distribution to guarantee that the initial generated interference is below the target. This way the algorithm remains as in Figure 4.2 with an alternative step of setting the Tx psd to achieve a minimum SINR. Then the algorithm can function properly with a positive step of power, but the convergence should be the same as if the starting distribution is random and the negative step of power is also considered.

With this last consideration, it is possible then to test the algorithm. The results are shown in the following section. The default system parameter are shown in Appendix (A).

4.3 Results

The first result to be evaluated is the convergence of I_{lev} because the metrics are constructed based on its information. Following is the effect of the parameters I_{lev} and the minimum SINR distribution, and last the technique's performance.

4.3.1 Interference Convergence

Before verifying the convergence, it is worth expressing some conventions. I_{lev} and consequently the received interference are expressed in IoT by normalizing to the thermal noise, so results are easier to analyze and compare. The average interference distributions shown consider one sample per each BS (More details on Appendix B), so the expected result is an average interference per BS equal to I_{lev}.

The cdf in Figure 4.3 shows the result for the two metrics with I_{lev} set to 13 dB. The average IoT converges to the same value for both, with a standard deviation of of 2.37 dB for M_1 and 2.45 dB for M_2. The initial power distribution is set to the minimum.

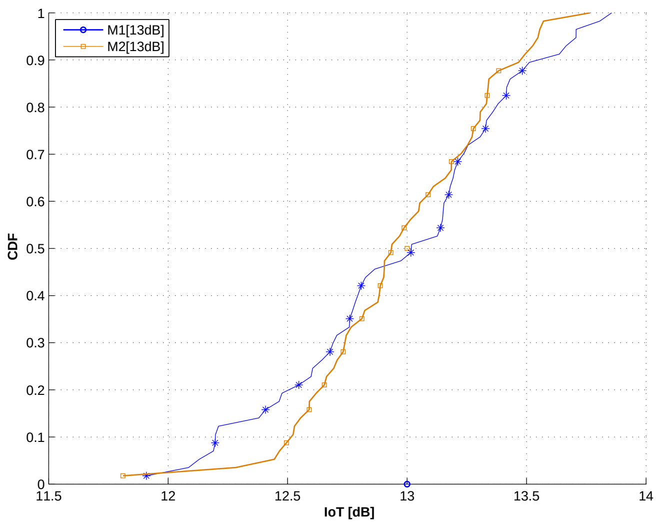

Figure 4.3: Convergence to IoT level - The cdf of the IoT obtain for both metrics show that the average IoT is successfully reached

This result indicates that the convergence is in average obtained, and as such, the "gain" estimations are adequate because each BS experiences a similar IoT which is in average the I_{lev} set as target. The attractive idea is that the interference is controlled, and the algorithm functions appropriately as a consequence of this.

The impact of the variability on the metrics affects equally to all users within a cell. When their throughput is mapped, an error is produced due to the estimate of interference. This affects the selection of the best candidate in each cell. This is left aside, however, as the interest is to find a performance of certain level compared to FPC. The results are presented having this consideration present.

4.3.2 The effect of Ilev

The algorithm is tested for a wide range of I_{lev}. Nevertheless, from previous results it is expected to have a good performance with the IoT levels obtained in those cases. I_{lev} can then be studied initially from 1 to 20 dB to evaluate its impact.

The interference generated by each cell is proportional to the power used for transmission among users served by it.I_{lev}, could be seen as a an interference budget for each cell, allowing to conclude that the higher the budget is, the more users would get to power up, improving the cell performance. On Figure (4.4) the performance of Outage and Cell thrughput for the range of I_{lev} mentioned verifies this.

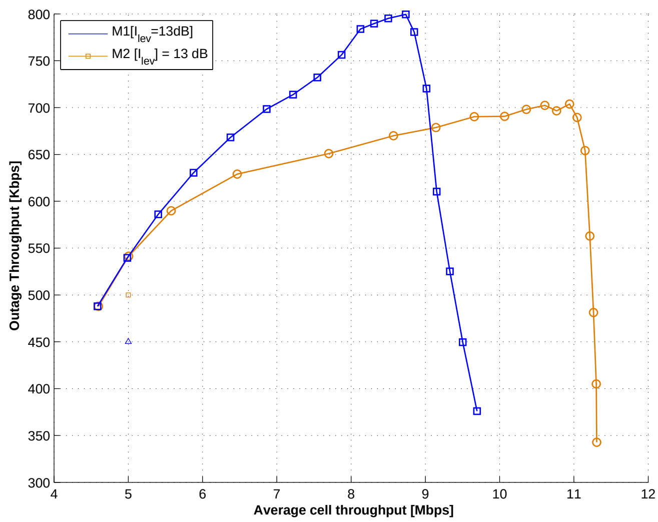

Figure 4.4: Impact of I_{lev} on the Outage vs Cell KPI - Constat increases of 1 dB show a grow for both until outage finds a peak

Both cell and outage throughput show an increase for each step given to I_{lev} (each dot represents a value of it) until the outage users experience a drop in the performance. The result for M_1 shows a faster drop than that of M_2.

Effectively, one metric is oriented to the outage while the other is oriented to optimize the total cell throughput. Besides, it is seen how the effect of this parameter is similar to that of P_0 and I_0 on the previous techniques, it is proportional to the Tx power distribution for all users.

4.3.3 Minimum SINR Effect and Starting power distribution

The system is simulated first with the two proposed metric. The resulting cdf of the SINR is extracted and shown (Figure 4.5) using the initial minimum power distribution and a target I_{lev} of 12 dB.

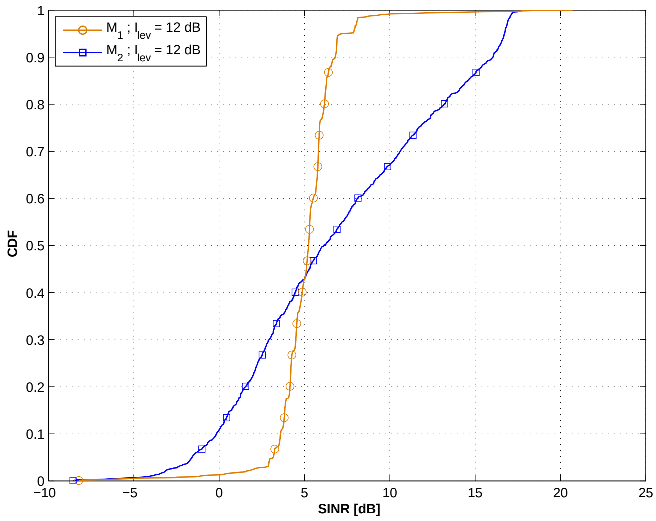

Figure 4.5: SINR distribution for metric 1 and 2 - The outage is too penalized for cell oriented metric, and average cell SINR is lower for user oriented

Interestingly, the user oriented metric, M_1 tends to gather the most probability around 5 dBs, with a very low differentiation of user experienced SINR. The reason algorithmically, is that as soon as the trade off of a given user starts being low others would result better candidates, but after these are powered up too, the previous may become the best candidate again.

It should be noted how the SINR distribution is similar to that obtained with the full compensation case of FPC.

The cell oriented the metric, M_2, shows more than 40 % of UEs are experiencing SINR below 5 dB, while it achieves higher probability for higher SINR when compared to the previous metric. It is also noted that almost no user above16 dB. This is attributed to the gain, because the throughput mapping yields practically not difference around these values.

This results leads to an important conclusion: to provide with a desired coverage, the cell performance has to be penalized because there is a subset of UEs that inevitably increase the interference they generate in order to increase their performance and in the system point of view the interference has more impact.

Minimum SINR effect

The purpose of setting a minimum SINR is to force users experience no less than a desired level of performance, most likely due to outage requirements. For the CIPC point of view, it means that some UEs are powered up from their initial minimal power distribution regardless of their gain and cost trade off.

It is possible to set a minimum SINR using the estimator I_{lev} in the cell. The results of doing this with a minimum SINR of 2 dB and 6 dB are observed in Figure 4.6, for both metrics.

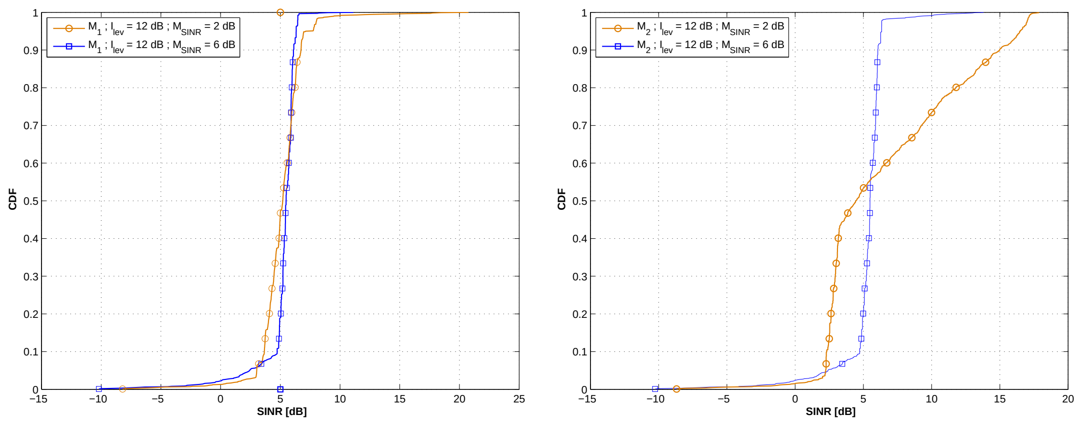

Figure 4.6: SINR cdf for metrics 1 and 2 with minimum SINR 2 and 6 dB - The outage performance is vastly improved for 2 dB but if the SINR target is too high it may cause the technique to not converge

The results show a mean of 12 dB on the average cell IoT for the case of minimum SINR 2 dB and both metric result in 13.73 dB in average cell IoT for the minimum SINR of 6 dB. There are several conclusions that can be extracted from this result:

- If the initial power distribution is too high (minimum SINR of 6 dB), the algorithm does not converge to the set I_{lev}, and thus the interference and degradation of the system performance is high. This explains why for both metrics the cell IoT results in the same level: when the selection of the best candidates start, the generated interference is already above target. In fact there is never a candidate chosen.
- The minimum SINR of 2 dB, does not affect the previous result of M_1, since it was already resulting in a distribution where the probability of experiencing an SINR below this value is very low.
- For the metric 2, a vast increase in outage performance is obtained, while the probability in the higher SINR values decreases. The sacrifice of the cell throughput in favor of the outage is once again verified.

The effect of the minimum SINR target can be also expressed in terms of throughput. In Figure 4.7, the system is simulated using M_2 and various minimum SINR targets. The same conclusion derived from the SINR distribution can be done.

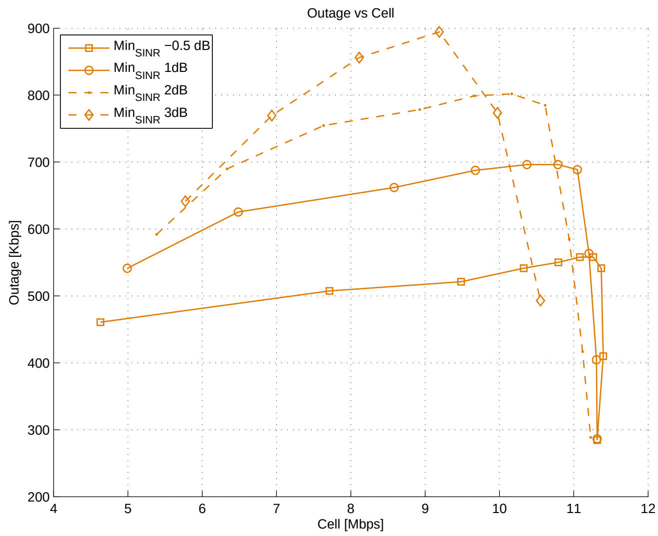

Figure 4.7: Min SINR effect for metric 2 - The effect is analogous tho that of α in FPC

Then it can be concluded that the minimum SINR gives a mean to tune the outage performance scarifying the cell throughput. This should result familiar, since it is the same effect achieved with α on FPC and β on the G-IPC. With these two tunning parameters, I_{lev} and the minimum SINR, it is possible to look for operating points to obtain a final reference performance.

4.3.4 CIPC Performance

The performance of M_1 does not show any potential gain when compared to G-IPC and no improvement of interest when the minimum SINR is applied, reason for why it is left behind. The focus is then on M_2. The analysis of the minimum SINR, shows that there are performance cases of interest, in Figure 4.7 specifically for the cases of SINR min 2 dB and 3 dB. These two cases can be directly compared to the ones obtained in G-IPC choosing the peak outage cases. These are $I_{lev} = 10.59dB$ and $I_{lev} = 11.24dB$ respectively.

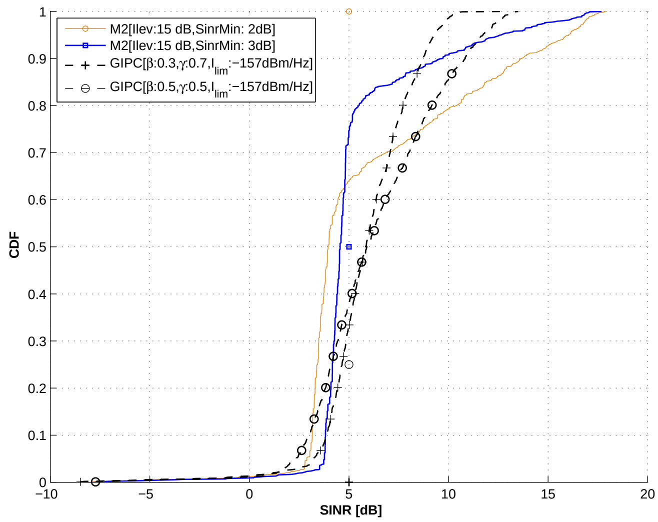

Figure 4.8: SINR cdf for metrics 1 and 2 with minimum SINR 1, 3 and 9 dB - The outage performance is vastly improved for 1 and 3 dB but if it's too high it may cause the technique to not converge

The essential difference in SINR (Figure 4.8) distribution is of particular interest. It is best described dividing it in regions.

First dividing the curves described by CIPC in three regions. The region of the lower SINR is determined by the minimum SINR target a low probability is found on it.

The middle SINR region, contains most of the UEs (60 % for $Min_{SINR} = 2dB$ and and 75 % for $Min_{SINR} = 3dB$) and represents candidates that are chosen less frequently (if at all). The percentage of UEs around this area is proportional to Min_{SINR}.

The higher SINR region shows more percentage of users than the cases of G-IPC, pointing that there, trade off is the highest. In fact the previous region "breaks" for a given percentile of the CDF that is proportional to the minimum SINR. This is because the "budget" decreases when the initial power distribution generates more interference. Then, less candidates can be selected to be on the third region.

MIN_{SINR} defines the spreadness of the SINR's CDF, if it is high, it improves the first region, outage performance. Previous techniques' results have shown that the cell outage performance is degraded when the IoT levels arise. For those, the peak outage operational point is found by tuning P_0 or I_0, which directly increases the Tx psd of all users in the system. It was proven that the optimum outage is related to the power limitation experienced by them. The reason was that the constant increment of the parameters results in an increase in performance for all UEs that are able to do it. As soon as the outage finds the limitation, instead of increasing its performance it just experiences a higher interference due to all others who could do the increment.

In this technique, the increment in I_{lev} and minimum SINR does not imply an equal increment in the Tx psd.

Interestingly, the tolerance of the outage throughput to the IoT levels is very similar to the cases obtained for G-IPC. In fact, around 14 dBs (Figure 4.9) the outage throughput starts being practically the same. In the figure, it is remarked how the difference in throughput is at maximum 5 % and 7.5 % for the same IoT levels.

The Tx power distribution shows how the percentage of UEs experiencing the maximum power limitation is very similar to G-IPC case.

Summarizing, the peak outage operational points are sustained to the same conditions of power limitation even though the techniques distribute the power in a totally different manner, in fact one is open loop while the other is closed loop.

Also, observing the Tx power distribution points that for CIPC the probabilities are greater for the low SINR values compared to G-IPC. However the average IoT remains on the same level. This is very important, since it indicates that the power is being distributed in a "smarter" manner. A better performance in outage is obtained generally with less Tx power, which is very positive in the user point of view.

Table 4.2 summarizes the performance of the operating points compared to the previous techniques.

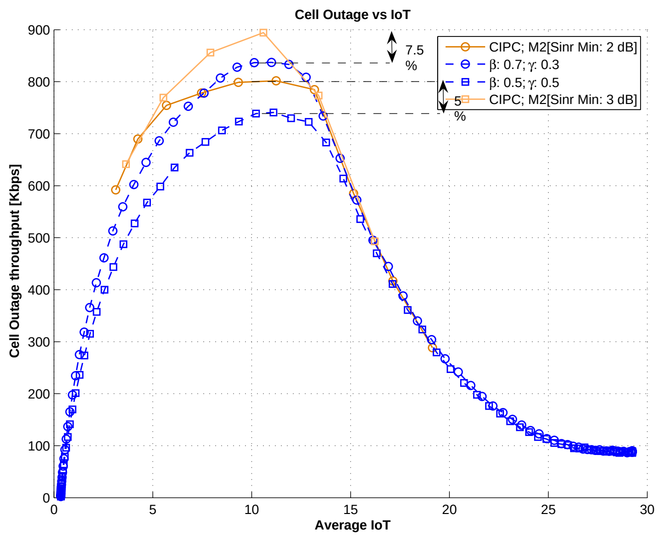

Figure 4.9: Output throughput vs average IoT - Higher outage throughput is achieved with the same IoT levels when compared to GIPC

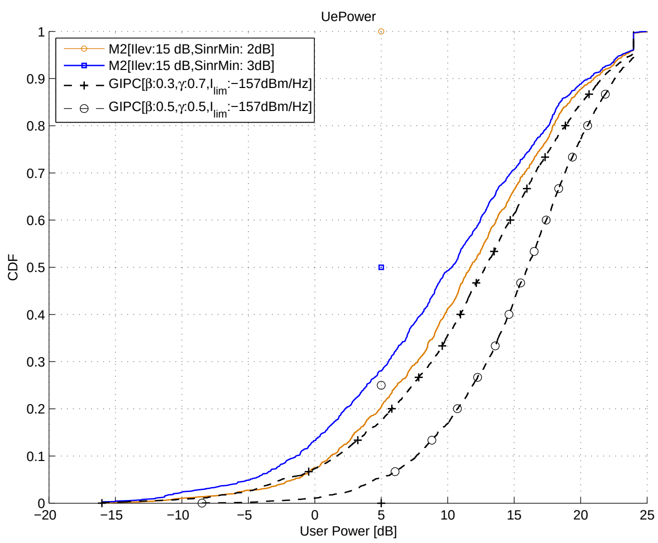

Figure 4.10: UE Transmitting power distribution, C-IPC metric 2 - The concentration is in the lower region

Ref	I_{lim} [dB]	**Min SINR [dB]**	**Cell [Mbps]**	**Gain over Ref [%]**	**Outage** [Kbps]	**Gain over Ref [%]**	**Av IoT [dB]**	$IoT_{ref} - IoT$ **[dB]**
FPC_1	10.59	1	11.05	4.8	688.7	22	13.67	1.3
FPC_2	11.24	2	10.62	11.9	785	(-2.7)	11.91	3.09
$GIPC_1$	10.59	1	11.05	5.84	688.7	(-1)	13.67	1.3
$GIPC_2$	11.24	2	10.62	11	785	(-1)	11.91	3.09

Table 4.2: Summary of reference operating points compared of all techniques

4.4 Conclusions

The results of this technique show a very similar behavior to the past when it comes to IoT levels, power limitation and the performance of Outage and Cell throughput. This leads to formulate several common conclusion. First, there is always a compromise between the cell throughput and the outage. If it is the wish to increase the throughput of the outage for example, the price is paid in total cell throughput, and vice versa. Moreover, the outage UEs are consistently experiencing a power limitation that prevents them from achieving the same gain as the cell center UEs. Instead, there are peak points after which their performance drops, attributed to the fact that the power up in the system is translated to them only as an interference increase.

The gain of CIPC over G-IPC is below 12 % on cell throughput while keeping the same outage . When compared to the original FPC cases, the gain over FPC is up to 22 % for outage, keeping the same cell throuhgput. The difference between optimal point on refference work [(9)] and α : 0.8, is considerable, in percentage. The improvement over the second is lower. Regarding the tunability of the technique, the use of metrics is translated in a higher degree of freedom than the other techniques.

The definition of the metric may vary depending on the interest. The two metrics analyzed here, are good examples of how they can be conceived as cell or user oriented. On the other hand, the minimum SINR can be used to “tune” the outage.

Finally, it is concluded that this technique not only improves FPC in the reference operational points, but it also defines an area of operating points that is superior in outage and cell compared to FPC, and even G-IPC. With the cell metric proposed, the Tx power is distributed smartly, because even if it is lower than the others, the rates achieved are higher. The reason for such improvements is the inclusion of a direct measure of the actual gain perceived by a user when its Tx psd is set and the inclusion of an estimated cost, which is the interference.

5

Conclusions

This chapter summarizes the main conclusions of this work and presents further practical considerations along with related future work.

5.1 Conclusions

This thesis is focused on the power control of a EUTRAN LTE cellular system, corresponding to the uplink direction of the 3GPP Long Term Evolution Project.

In the current standardization process, the power control is specified to function both with open loop and closed loop mechanisms. The open loop functioning is based on the Fractional Power Control technique which is designed to allow for full or partial compensation for the pathloss. On the other hand, the algorithms used to implement the closed loop term are vendor specific and still under research.

The first scope of this project is to study the FPC technique in a detailed manner to obtain a reference performance. The second scope is to propose novel PC techniques based on the possibilities given by the closed loop term, comparing the performance with the reference obtained for FPC.

Thus, two different PC techniques are proposed. Each presented in the order of thought, and each inspired on the results of the preceding. A tool is developed to model the system in a static way, neglect the effect of some of the RRM functionalities and focus on the power control. Then, the proposed techniques are tested and compared with the key performance indicators.

The first proposed technique is the Generalized Interference Based Power Control. It introduced the use of information of the pathloss to non serving BS of a UE when setting its power. This (inter-cell) pathloss is a measure of the interference the user can generate. The results of the technique shows up to 28 % of gain of outage throughput while keeping nearly the same average level. Also, it is found that the outage performance is optimized with lower interference levels and with lower Tx power distribution when compared to FPC. Different gains in both outage and cell may be achieved by tunning its parameters.

It is verified that the optimum outage performance is achieved when the subset that represents it are transmitting nearly or with the maximum power allowed, a property that depends on the value of one of its parameters (γ). Finally, it is seen that operating points that result in more percentage of UEs experiencing high SINR do not provide high gain due to the SINR to Throughput mapping.

The second proposed technique is the Cell Interference Based Power Control. It is based on estimating a gain and a cost per increase of Tx psd, where the gain is measured directly in throughput rather than SINR. This results in a PC algorithm that has an "interference budget" handled by distributing power in the minimum step of 1 dB to those UE that represent the best trade off between their potential gain and cost. The fact that the algorithm allows to estimate the performance of each UE before setting the power, introduces the possibility to set the Tx psd of the users to provide with a minimum SINR.

The algorithm shows a high degree of tunability. The trade off between gain and cost is expressed with the use of metrics, which can be defined in many ways.

The results show an improvement also in both cell and outage, with a maximum 22 % gain in outage and 5 % of gain in average. The tunability allows to set other gains below this margin with the metrics used. It also shows an even lower IoT and UE Tx power distributions when compared to FPC and IPC, effectively improving the PC functioning gain both system and user point of view. Moreover, with the means of the minimum SINR it is possible to set a compromise between the cell outage and cell throughput performance that is desired to maintain a given coverage.

In conclusion, the CIPC is considered a good PC technique since it features a cell autonomous mechanism that controls the interference and sets the UEs to transmit with a psd according to the gain in throughput they would generate. The technique offers an appropriate criteria on how the closed loop term of the UL standardized PC could be used. It also offers a high degree of tunability to compromise the cell outage and cell performance.

As general conclusions, it has been observed that the improvement of outage throughput comes with a sacrifice of the cell throughput and vice versa. All the techniques allow a tune of this, in different manners. The last technique, the CIPC, achieves performances that improve booth cell and outage throughput with lower interference and Tx power levels, which indicates that in this case, the power is smartly distributed among users.

5.2 Future work

During this thesis PC techniques were analyzed by the means of a fixed bandwidth, balanced load and average calculations on a static simulator. Most of the RRM functionalities are neglected to focus the study of PC. Nevertheless, there are still open aspects that could be studied under the same assumptions.

Implementation issues

The algorithms proposed use information about PG_I that is assumed to be known at the BS since there are feedbacks obtained from the UE, closing the loop of the PC. However, it is known that the information of pathloss to all non serving BSs is not provided on the standards. In the reference it can be seen that for Hand Over reasons, only the the second lowest pathloss is included.

Future work could investigate the impact this have. Additionally, the impact of errors in such measurements could be analyzed, since the means to obtain such signal are already standardized.

Including the inter working with other RRM functionalities

Most of the RRM functionalities were neglected in the simple model assumed for work. However, potential gain provided by the techniques may be achieved by inter working with some of them. A simple example is the possible exploitation of the interference "control" achieved with both algorithms (GIPC and CIPC) by the use of

Interference Coordination (IC) algorithms in the PS.

Analyze the impact of different types of traffic and load conditions

The scenario analyzed here assumed balanced load conditions. Unbalanced conditions would imply a different amount of users per cell in the system which should affect the performance of the system.

It could be assumed that the CIPC would perform better since each cell is able to adapt autonomously, but the assumptions made in the algorithm may still lead to errors. It should be noted that the reference performance of FPC concerning this is also needed.

The different traffic models are also a key factor to analyze PC. The conceptual assumptions in this work could correspond to a full buffer in practice, where the users have an indefinite amount of data to transmit. With RRM functionalities and a finite buffer (low amount of data to transmit per user), it is expected that the call duration varies significantly among users.

The PC technique deployed could play an important role on this since it can define the performance of the users, which will determine their duration in the system. A detailed study of this and comparison of all the techniques of obvious importance.

Automatic setting of parameters

Finally it has been observed that the interference levels are similar among techniques when comparing to a similar operational point (e.g. the peak outage). On the other side, the parameters of each technique, including FPC, are meant to be set by the operator.

An important contribution would be to find a mechanism to automatically set the optimum parameters. One approach could be using the interference levels.

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Appendix A

System model and default simulation parameters

This appendix overviews the most relevant aspescts of the system model, showing its layout and the assumptions made to simplify the analysis the power control of EUTRAN LTE Uplink, as one of the RRM functionalities at link layer level. It also summarizes the default system parameters used for simulations through the thesis. If any result uses a different parameter it is explicitly remarked.

A.1 Macro-cell Scenario

Following the 3GPP guidelines [(1)], the cell simulation layout consist of a Macro-cell scenario refference case 1. Composed by a grid of 19 sites with 3 sectors each. The site refers to the area covered by one eNB and the sector to the area covered by one of the three sectorial antennas contained on it. The distance between sites is 500 meters and each sector is modelled by a hexagon, as illustrated in Figure A.1 (left). Note that During the work the sectors are reffered to as Base Stations (BSs).

The operating bandwidth is divided in 50 PRBs with a bandwidth of 180 KHz each. There is a Maximal Ratio Combining (MRC) in the specifications, used to constructively combine the multiple received signals in the antennas. It is modeled here as a constant gain of 3 dB in the received signal.

The total pathloss between an UE and a BS is modeled as:

$$P_L = L_R(d) + A(\theta) + SF \qquad [dB] \tag{A.1}$$

Where:

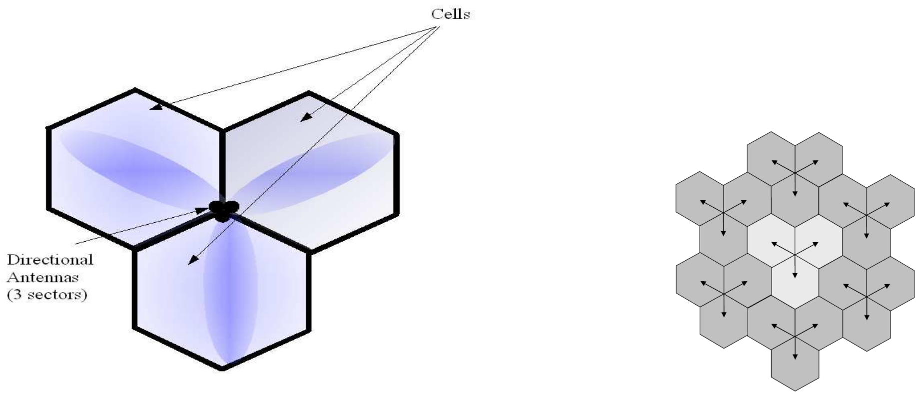

Figure A.1: Simulation site and system representation - Each site consists of 3 antennas each covering an hexagonal sector. The secotrs are reffered to as BS. The system is composed by 19 sites

- $L_R(d)$**:** is the pathloss between the BS and the UE dependant on the distance d.
- $\mathbf{A(\theta)}$**:** is the modeled antenna gain pattern, dependent on the angle θ between the UE and the BS. It has only one lobe with a maximum attenuation of 20 dB.
- **SF:** Is the shadowing, modelled as a log-normal distribution with mean 0 dB and standard deviation 8 dB.

Equation (A.1) assumes a bidimensional model of the spatial representation of UEs and BSs and the time unvariant [(18)].

A.2 System simulation

The results of the algortithms proposed have been obtained through a static link level simulator developed by the author and using inputs from a Nokia Siemens Networks proprietary System Level Simulator. The first is a simplified tool that focuses on the power control link level calculations that uses an input containing a list with information about UEs and BSs. This information regards the coordinates, related pathloss, antenna patterns, and others). The static simulation offers low complexity and fast calculations, making it able to generate results faster than the system level simulator.

Wrap Around

The simulation layout is represented in Figure A.1 (right) where each BS functions with an independent power control.

The interference patter would not be uniform for this layout as the ceter have more interfering neighbours in all directions when compared to the cells in the borders. This situation is to be avoided for the effect of average interference calculations used in the static tool.

The pattern is then made uniform using Wrap Around (WA) . This affects the total pathloss P_L calculation by considering alternative BS and UE locations. Visually, it consists in repeating the original cell layout on each side of the original one, better expressed in Figure [A.2]. There is a pathloss information for each potential link between a BS and any UE. From the UE point of view, the same site is placed at different positions, like if the cell layout was wrapped around a bowl.

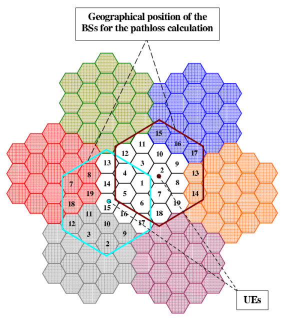

Figure A.2: Wrap Around representation for the system - Each BS has mirrors, the pathloss between a UE and a BS is taken as the lowest between the original and each mirror

The new version of the same site (those outside the 19 ceter sites) are called mirror sites. The total pathloss from a UE to a BS is then calculated using the closest mirror site position.

User Generation

The sytem level simulators is used to generate an uniform distribution of users per cell. The distribution is equally balanced in the system, where each cell has the same ammount of users. To make the average calculations precise 100 users are generated per cell, giving a total of $100 users/cell \cdot 3 cells/site \cdot 19 sites = 5700 users$. The serving BS of a given UE is taken as the one that is assosiated with the lowest total pathloss to it P_L.

Noise model

Thermal noise has been modeled [(18)], which has a constant power spectral density over the working frequency. It's level is $N = -174dBm/Hz$, which doesn't vary in time.

Throughput mapping

In EUTRAN LTE UL, the MCS is chosen according to the estiate of SINR, higher orders are used when this is higher. Since the simulation is static, a fit is used to model such selection. Figure A.3 shows how the different MCS are selected according to the experienced SINR and the resulting BW efficincy. To apropiately model the different MCS, a fit of the shannon capacity expression is applied to fit the resulting BW efficiency, according to the conclusion of one of the reference work [(13)], Equation (A.2) shows how the throughput is calculated for a given user from its experienced SINR and allocated bandwidth.

$$C = BW_{eff} \cdot \nu \cdot M \cdot BW_{PRB} \cdot log_2(1 + (\frac{S}{S_{eff}})) \qquad [Bps] \tag{A.2}$$

Where:

- BW_{eff}**:** is the bandwidth efficiency. Set to 0.72.
- ν**:** is a correction factor Set to 0.68.
- **M:** is the number of allocated PRBs.
- BW_{PRB}**:** is the bandwith of one PRB. Equal to 180 KHz.
- **S:** is the user experienced SINR
- S_{eff}**:** is the SNR efficiency at system level. Set to 0.2 dB

A.3 Default System Simulation Parameters

The default system simulation parameters are shown in Table A.1. The simulations all assume Fixed Transmission Bandwidth (FTB) .

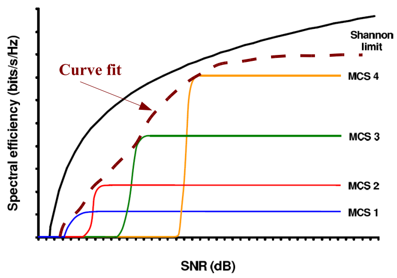

Figure A.3: System's modeled BW efficiency - The PS is neglected through a static simulation, this model relates the user throughput SINR

Parameter	Value	Unit
Bandwidth efficiency	0.72	-
Bandwidth of PRB	180	KHz
Maximum UE P	250	mW
υ		-
Number of PRBs per UE	6	-
Outage	5	%
PC range	40	dB
Sinr efficiency		dB
Thermal Noise level	-174	dBm/Hz
Total number of PRBs	48	-
Users per cell	100	-
MRC gain	3	dB
FPC		
a	0.6	-
P_0	-57	dBm
GIPC		
g	1	-
b	0	-
I_0	-157	dBm/Hz
CIPC		
I_{lev}	13	dB
Min SINR	2	dB

Table A.1: Default simulating Assumptions

Appendix B

KPI calculation

This appendix briefly explains how the KPIs are calculated using the static simulation. The power distribution (the first KPI) is set accoring to the mechanism described by each PC technique and the power limitations. For the purposes of this appendix, the TX psd of each user is assumed to be already set.

B.1 IoT calculation

In Appendix A it was described how each UE is assosiated with a total pathloss to each BS in the system (57 in total), where the strongest is taken to be the pathloss to the serving BS. To express it, the term $pg_{i,j}$ denotes the pathgain (inverse of pathloss) of user i to BS j.This way, the user i received power spectral density at its serving BS (referred to as signal) can be modeled as in Equation (B.1), for a given instant.

$$rsd_i = psd_i \cdot pg_{i,s(i)} \qquad [mW/Hz] \tag{B.1}$$

Where s(i) is the BS serving user i. Note that due to the specifications, the transmitting power spectral density psd_i is constant for each transmitted PRB, allowing to make this calculation undependantly of the allocated bandwidth.

The interference spectral density isd_j perceived by a given BS can be expressed similar to the previous, adding the received signal of the users which it is not serving (Equation (B.2)).

$$isd_j = \sum_{k=\bar{s}(j)} psd_k \cdot pg_{k,j} \qquad [mW/Hz] \tag{B.2}$$

This expression however, is valid only for a given PRB. Where $\bar{s}(j)$ denotes the users not served by BS j and allocated to transmit on the observed PRB. The approach for the static simulation is to calculate the average received interference spectral density of one PRB assuming that all UEs in the system are allocated to transmit on it (Equation (B.3)), this scaled to the entire working bandwidth.

$$\tilde{isd_j} = \sum_{k=\bar{s}(j)} E[psd_k] \cdot pg_{k,j} \qquad [mW/Hz] \tag{B.3}$$

This effectively neglects the functionality of the PS. Conceptually it corresponds to the case of a 100 % usage of the transmission bandwidth in each BS, with a constant interference spectral over it. $\tilde{isd_j}$ is the average interference spectral density received for the average Tx psd of all the users in the system.

Then the second KPI is defined per cell j as the ratio of the interference plus the thermal noise level normalized to the second as Equation (B.4) shows.

$$IoT_j = \frac{\tilde{isd_j} + n}{n} \qquad [-] \tag{B.4}$$

N is the total Thermal Noise power density received by the antenna.

B.2 SINR calculation

Due to the static simulation. the user experienced SINR is calculated also as an average. The estimator used for it is expressed in Equation B.5. Where a "snapshots" approach is used. It consist in obtaining the average for a large set of different configurations of interference per BS.

$$\tilde{sin_i} = E[\frac{rsd_i}{isd^K_{s(i)} + n}] \qquad [-] \tag{B.5}$$

Where $isd^K_{s(i)}$ is the sample K of theinterference spectral density perceived by the BS serving user i. The samples are constructed with a random selection of 1 user per cel each. Note that the received psd is constant due to non mobility and no channel variation.

The reason for using this estimator and not the previous calculation for interference is better explained with Equation B.6

$$E[\frac{sinr_i}{isd^K_{s(i)} + n}] \neq \frac{E[sinr_i]}{E[isd^K_{s(i)} + n]} \qquad [-] \tag{B.6}$$

B.3 Cell Throughput Calculation

With the user experienced SINR and the allocated bandwidth, the user throughput mapping described in Equation (A.2) is calculated here. Now expressed as T_i. Then the third KPI, the average cell throughput of BS j, is calculated as expressed in Equation (B.7).

$$\tilde{CT_j} = E[T_s(j)] \cdot UE_{TTI} \qquad [bps] \tag{B.7}$$

Since there is a high number of user per cell generated (more than what could be allocated in a single Transmission Time Interval -TTI-), the average user throughput is taken and then multiplied by the number of users allocated in a single TTI. UE_{TTI}. This las parameter is calculated as Equation B.8.

$$UE_{TTI} = \frac{UE_{Cell}}{N_{PRB}} \qquad [-] \tag{B.8}$$

Where UE_{Cell} is the number of users generated in a cell (constant) and N_{PRB} is the number of PRBs on the working bandwidth.

The last keyperformance indicator, the outage throughput is taken to be the 5 % point of the Cumulative Distribution Function of the distribution of user thoruhgput T_i.