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Power Control and Energy Efficiency Strategies for D2D Communications Underlying Cellular Networks

Master of Science Thesis

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Controle de potência e estratégias de eficiência energética para comunicações D2D subjacentes redes celulares

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POWER CONTROL AND ENERGY EFFICIENCY STRATEGIES FOR DEVICE-TO-DEVICE COMMUNICATIONS UNDERLYING CELLULAR NETWORKS

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Contents

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"I have learned that a man only has the right to look down on another man when it is to help him to stand up."
Gabriel José García Márquez

Abstract

In a world where people count on their smartphone, smartwatch, tablet and other devices to keep them connected wherever they go, they expect its application to run without problems, such as dropped calls, slow download and choppy videos.

In this context, Device-to-Device (D2D) communication represents a promising technology, because it is a direct and low-power communication between devices close, allowing to offload the data transport network, increase spectral and power efficiency. From the subscriber point of view, D2D means to use applications without problem and increase battery life. However, in order to realize the potential gains of D2D communications, some key issues must be tackled, because D2D communications may increase the co-channel interference and compromise the link quality of cellular communications.

This master's thesis focuses on Radio Resource Management (RRM) techniques, especially Power Control (PC) schemes, to mitigate the co-channel interference for D2D communications underlaying a Long Term Evolution (LTE) network, aiming at the reduction of the intra- and inter- cell interference and at the improvement of energy efficiency. The main PC schemes (e.g. OLPC, CLPC and SDPC) and a hybrid scheme (CLSD) are calibrated and used in macro- or micro- multicell scenario, using different loads and imperfect Channel State Information (CSI). In addition, the impact of downtilt is analyzed, which is used to adjust the coverage radius of an Evolved Node B (eNB) and reduce co-channel interference by increasing cell isolation.

The numerical results indicate that PC schemes and downtilt, duly calibrated, can provide gains to cellular and D2D communications. In other words, D2D technology can be used to further increase the spectral and energy efficiency if RRM algorithms are used suitably.

Keywords: Device-to-Device (D2D) communication, Long Term Evolution (LTE) network, Power Control (PC), Downtilt, Interference management, Energy efficiency

Resumo

Em um mundo onde as pessoas contam com *smartphone*, *smartwatch*, *tablet* e outros dispositivos para mantê-las conectadas onde quer que vão, todos esperam que seus aplicativos sejam executados sem problemas, tais como chamadas abandonadas, *download* lento e vídeos com saltos.

Neste contexto, comunicação dispositivo-a-dispositivo (do inglês, Device-to-Device (D2D)) constitui uma tecnologia promissora, pois é um tipo de comunicação direta e utiliza baixa potência entre dispositivos próximos, permitindo-se desviar o tráfego da rede móvel, aumentar a eficiência espectral e de potência. Do ponto de vista do assinante, D2D significa usar aplicação sem problemas e aumentar o tempo de vida da bateria do celular.

No entanto, a fim de realizar os ganhos potenciais das comunicações D2D, algumas questões-chave devem ser abordadas, pois as comunicações D2D podem aumentar a interferência co-canal e comprometer a qualidade do enlace das comunicações celulares.

Esta dissertação foca em técnicas de Gerenciamento de Recursos de Rádio (do inglês, Radio Resource Management (RRM)) para mitigar a interferência co-canal para comunicações D2D que se baseiam na Evolução de Longo Prazo (do inglês, Long Term Evolution (LTE)), visando a redução da interferência intra- e inter-celular e na melhoria da eficiência energética. Os principais esquemas de Controle de Potência (do inglês, Power Control (PC)) (e.g. OLPC,CLPC e SDPC) e um esquema híbrido (CLSD) são calibrados e utilizados no cenário macro ou micro multicelular, usando diferentes cargas e Informação do Estado do Canal (do inglês, Channel State Information (CSI)) perfeita ou imperfeita. Além disso, o impacto da inclinação da antena (*downtilt*) é analisado, que é usada para ajustar o raio de cobertura de uma Evolved Node B (eNB) e reduzir a interferência co-canal, aumentando o isolamento de células.

Os resultados numéricos indicam que os regimes de controle de potência e inclinação da antena, devidamente calibrados, podem fornecer ganhos para a comunicação celular e D2D. Em outras palavras, a tecnologia D2D pode ser utilizada para aumentar ainda mais a eficiência de espectro e a eficiência energética se algoritmos de RRM forem utilizados adequadamente.

Palavras-chave: dispositivo-a-dispositivo (D2D), Redes LTE, Controle de potência (PC), Inclinação da antena (*Downtilt*), Gerenciamento de interferência, Eficiência energética

List of Figures

List of Tables

Notation

Acronyms

3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
BLER	BLock Error Rate
BS	Base Station
CDF	Cumulative Distribution Function
CLPC	Closed Loop Power Control
CLSD	Closed Loop Soft Dropping
CPU	Central Processing Unit
CoMP	Coordinated Multi-Point
CSI	Channel State Information
D2D	Device-to-Device
DIST	Distance-based Grouping
DL	Downlink
eNB	Evolved Node B
EPA	Equal Power Allocation
GSM	Global System for Mobile Communications
GPL	GNU General Public License
IMT	International Mobile Telecommunications
ITU	International Telecommunication Union
LTE	Long Term Evolution
LSI	Large-Scale Integration
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MR	Maximum Rate
MS	Mode Selection
MSE	Mean Squared Error
NLOS	Non-Line of Sight
NMSE	Normalized Mean Square Error
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OLPC	Open Loop Power Control

PAIR	D2D Pair Gain-based Grouping
PC	Power Control
PRB	Physical Resource Block
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QoE	Quality of Experience
QPSK	Quadri-Phase Shift Keying
RAN	Radio Access Network
RA	Resource Allocation
RET	Remote Electrical Tilt
RB	Resource Block
RM	Rate Maximization
RRA	Radio Resource Allocation
RRM	Radio Resource Management
RR	Round Robin
SCM	Spatial Channel Model
SD	Soft Dropping
SDPC	Soft Dropping Power Control
SINR	Signal to Interference-plus-Noise Ratio
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
VET	Variable Electrical Tilt
WCDMA	Wideband Code Division Multiple Access
WINNER	Wireless World Initiative New Radio
WPAN	Wireless Personal Area Network
WWAN	Wireless Wide Area Network

Chapter 1

Introduction

1.1 Motivation

The development of Radio Access Networks (RANs) has provided triple-play services (i.e. voice, video and data) anytime and anywhere. These features demand high spectral efficiency and so it is essential to ensure interoperability of radio access technologies and convergence of different services. Therefore, the International Telecommunication Union (ITU) has established a set of requirements for a high performance 4th Generation (4G) [1] of wireless communication systems. The key requirements are:

- high quality mobile services,
- user equipment suitable for worldwide use,
- user-friendly applications, services and equipment,
- worldwide roaming capability,
- compatibility of services within International Mobile Telecommunications (IMT) and with fixed networks.

Modern wireless networks e.g. 5th Generation (5G) need to be efficiently designed in order to support as much calls, data transmissions and mobile services as possible, and still extend the battery lifetime of User Equipments (UEs). Additionally, the successful operation of modern telecommunication systems is dependent, in part, on sophisticated real-time control mechanisms. Energy-efficient wireless networks have become an important research topic in the last years due to the increasing rate of data traffic and the quick growing of energy consumption [2].

Device-to-Device (D2D) communications underlaying a cellular network can improve resource utilization and potentially lead to a reduced power consumption. However, D2D communications may increase the co-channel interference and compromise the link quality of cellular communications [3]. Power Control (PC) is an important Radio Resource Management (RRM) functionality in wireless communication systems, which adapts the transmit power of the communicating devices to ensure a target Quality of Service (QoS) level, thus limiting interference and prolong the battery lifetime. Therefore, the design of PC schemes becomes attractive in order to keep interference under control, protect cellular communications, and get energy-efficient transmissions [4].

Another technique used to keep interference under control is called antenna downtilt, which is responsible for changing the antenna radiation pattern. By utilizing antenna downtilt, signal level within a cell can be improved and interference radiation towards other cells can be effectively reduced due to the antenna radiation pattern. However, an excessively large downtilt angle might lead to coverage problems at cell border areas. Therefore, it is vital to define a suitable downtilt angle [5].

1.2 Device-to-Device Communication

D2D is an attractive means of expanding mobile network capacity, user experience, energy efficiency and corverage. When a direct communication occurs between two UEs, this communication is called D2D. To provide high spectral efficiency, advanced techniques are needed to manage and control interference, because D2D users are added to cell.

D2D communication was first cited in [6] to allow multihop relays in cellular networks. Then others papers were published [7, 8], where the main investigated subject was the potential of D2D communications for improving spectral efficiency of cellular networks. Other potential benefits of incorporating a D2D communication in a cellular network is metioned such as peer-to-peer communication [9, 10], video dissemination [11], machine-to-machine (M2M) communication [12, 13] and cellular offloading [14, 15].

As mentioned above, D2D communications are added to the cells of a cellular sytem. Thus, it is important to understand how the resources are divided in the cellular network when D2D communication is used. D2D communication can occur on unlicensed spectrum (outband) or on cellular spectrum (inband). The inband technique can be subdivided in a group where all spectrum of cellular network can be used to cellular or D2D communication and another group where each communication uses a specific portion of the spectrum. These techniques are called, respectively, underlay and overlay.

There are works about inband and outband D2D communication in the literature [16, 17]. When D2D communication is used outband, the main problems are related to coordinating the communication over different bands due a second radio interface (e.g., WiFi Direct [16] and bluetooth [17]). Regarding the underlay case, until now, the main question is the problem of interference mitigation between D2D and cellular communications [18–20].

The features of the D2D are described below [16, 20]:

- **Unlicensed spectrum (outband)**: WiFi and Bluetooth operate in unlicensed spectrum, without any centralised control of usage or interference. This is not generally a problem when usage densities are low, but it would become a major limitation as proximity-based services proliferate. Throughput, range and reliability would all suffer;

- **Security**: The security features of WiFi and Bluetooth are much less robust than those used in public cellular systems. They would not be adequate for major public services and they would be unsuitable for public safety applications;

- **Radio resource management**: Unlike Bluetooth and WiFi, Long Term Evolution (LTE) operates in licensed spectrum and the radio resources are carefully managed by the network, to minimise interference and maximise the performance of the system. The same mechanisms can be extended to D2D;

- **Performance**: Direct communication between nearby devices may be able to achieve even higher throughput and lower latency than communication through an LTE base station. For example, the devices may be closer to each other than either of them is to the nearest base station and a busy base station may be a bottleneck. The network can still exert control over the radio resources used for these connections, to maximise the range, throughput and overall system capacity;

- **Spectrum reuse**: D2D could enable even tighter reuse of spectrum than can be achieved by LTE small cells, by confining radio transmissions to the point-to-point connection between two devices;
- **Network load**: Relieving the base stations and other network components of an LTE network of some of their traffic-carrying responsibilities, for example carrying rich media content directly between mobile terminals, will reduce the network load and increase its effective capacity;
- **Energy efficiency**: Integrating D2D into the LTE system provides the opportunity to achieve energy-efficient device discovery, for example by avoiding the need to scan for other wireless technologies, by synchronising the transmission and reception of discovery signals to minimise their duty cycle and by waking application software only when relevant devices are found in the local area. Meanwhile, direct transmission between nearby devices can be achieved with low transmission power.

1.3 RRM for D2D Communication

New challenges related with interference appear when D2D communications use cellular spectrum. Thus, it is necessary to improve and create RRM techniques for D2D communications such as mode selection, user grouping, Power Control and adaptive scheduling. This section gives an explanation about RRM for D2D communications, which are illustrated in Figure 1.1.

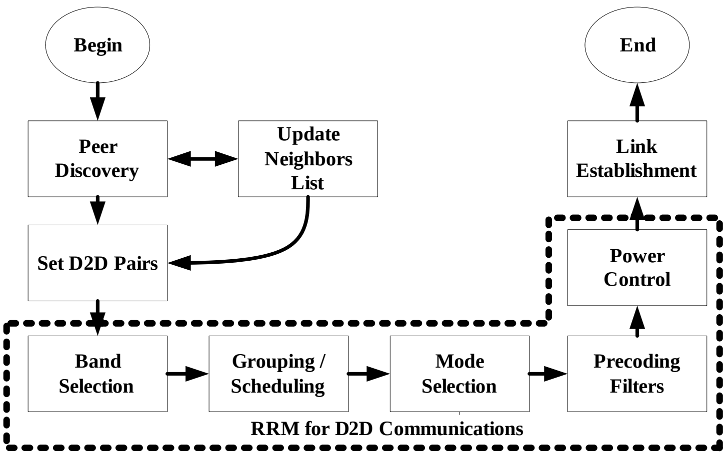


Figure 1.1: RRM techniques for D2D communications

1.3.1 Peer Discovery and Pairing

The goal of peer discovery is to look for UEs, which are candidates to establish D2D links. A UE or Evolved Node B (eNB) can be responsible for this procedure, in which they transmit beacon signals to identify its neighbors and analyze their beacon intensity. UEs have a higher probability to become candidate for D2D communication when their beacon intensity is strong. After the first step, the next step is the device pairing. Pairing is responsible for determining which D2D candidates establish D2D links in the cellular network [21]. The first and second step are well known in, for example, Bluetooth, where master node identifies in a range the devices wishing to participate of a specific connection [22].

1.3.2 Mode Selection

Mode Selection (MS) is an important RRM technique in D2D communication, which determines whether UEs can communicate directly or not (i.e. via the Base Station (BS)). In [23], the author proposes a mode selection procedure that takes into account the link quality of the D2D link and the different interference situation when sharing cellular Uplink (UL) or Downlink (DL) resources. The results ensure a reliable D2D communication with limited interference to the cellular network.

Other study about MS is realized in [24]. Therein, the author derives the system equations that can be used to analyze a system where both cellular communication and D2D communication can share the same resources. Via numerical analysis it was shown that communication mode selection needs to be designed carefully to prevent deteriorating the system performance. The results show that the main affecting factors for the performance gain from D2D are local communication probability and maximum distance between communicating devices. In other words, D2D communication is propitious when the UE is close to BS and the distance between the UEs of a D2D pair is short.

1.3.3 Resource Allocation

The purpose of the Resource Allocation (RA) is to select Physical Resource Block (PRB) of a set of available PRB for each transmission/reception in cellular or D2D communication. In [25], the authors use a method with which D2D communications can reuse the resources of more than one cellular user. The authors assume that PRBs can be selected with an optimal resource allocation method using the Channel State Information (CSI) of all involved links. The results show that the proposed method is the optimal method when D2D are located in most parts of the cell area and the method achieves better performance when the D2D pair becomes closer to the cell edge.

The Round Robin (RR) and Maximum Rate (MR) scheduling algorithms are well-known in literature and they can be used in D2D communication [26]. The principle of RR algorithm is to be resource fair with each user. It is accomplished by assigning the same number of PRBs to every user. The principle of Rate Maximization (RM) algorithm is to assign resources to the users which maximize system rate. The algorithm is performed for each PRB and resource are assigned the users with the largest channel gain on that PRB. The results showed that higher throughput gains are achieved when scheduling prioritizes the D2D mode due to proximity.

1.3.4 Grouping

The grouping is the key technique to achieve high reuse gains, because it is used to choose which cellular and D2D links should share a PRB. For example, it is possible to choose cellular and D2D users to share a resource randomly and, therefore, no channel information is used.

In [27], the authors developed several grouping algorithms. The Distance-based Grouping (DIST) algorithm's basic idea is to group the D2D transmitters that are farthest from the eNB with the scheduled cellular UEs as to obtain resource reuse gains without much losses to cellular communications performance. Therein, the D2D Pair Gain-based Grouping (PAIR) method is founded on the fact that the proximity between $D2D_{Tx}$ and $D2D_{Rx}$ is an important parameter for D2D communications and this aspect is prioritized for resource sharing. It is assumed that the large-scale fading gain for the link between these nodes is made available to the eNB, which uses it to represent the effective radio distance between nodes. This gain can be estimated and reported to the eNB by the $D2D_{Tx}$, $D2D_{Rx}$ or both.

1.3.5 Power Control

Improper use of transmit power can harm all previous blocks of RRM, because a high transmit power for a cellular or D2D transmitter can increase the interference level of system, decrease the QoS and reduce battery life. So, it is clear that PC schemes are important in traditional cellular network and become essential when D2D links are added to the network.

The D2D links have to adjust their transmit powers seeking to increase spectral and power efficiency, while cellular links keep a acceptable QoS. In [28], a dynamic PC mechanism is proposed to reduce interference generated by D2D communications and improve the performance of cellular communications in DL. The proposed algorithm has two phases. In the first phase, the eNBs assigns resources to D2D communications by reusing the same resources allocated to cellular UEs. Then, PC is usually applied for D2D communications to decrease interference to cellular UEs. For this goal, the eNB adjusts the transmit power of the D2D transmitter based on estimated channels gains between each desired link.

In [29], the authors consider that a cellular UE needs to communicate with an eNB in UL while multiple D2D links coexist in the common spectrum. Two forms of PC were proposed: centralized and distributed. Centralized PC occurs when D2D links are managed by eNB. In this case, the eNB needs to know the global CSI. The proposed distributed PC sets the transmit power of D2D-capable UEs based on the knowledge of direct link information and the minimum channel gain that is fixed and known by all UEs.

1.4 State of the Art

D2D communication is a technology used to improve QoS and Quality of Experience (QoE) of the users, while it provides the increase of resource utilization in cellular networks, because it can operate in licensed and unlicensed spectrum bands. In other words, D2D communications can underlay a cellular network, employing the same radio resource to improve the system efficiency. In a cellular network, where UE have traditional communications via eNB in a LTE system, UEs have the capacity to create a direct communication with each other over D2D links.

However, it is necessary to manage all these links and, for this purpose, the eNB becomes responsible for controlling the radio resources and set transmission parameters, such as, communication duration and transmit power.

There are several industrial and academic researches related with D2D communications, which show and explain the benefits of D2D communications to the next-generation of cellular networks, such as:

- provide a better energy efficiency;
- offload cellular networks;
- improve system capacity;
- increase coverage;
- improve QoS and QoE.

The combination of cellular and D2D communications opens several issues such as the analysis and design of techniques related to optimization, signal processing, decision theory and layer perspectives (e.g. physical, MAC, network and application). Figure 1.2 illustrates the main RRM procedures in a generic scenario with an eNB surrounded by UEs using cellular and D2D communications.

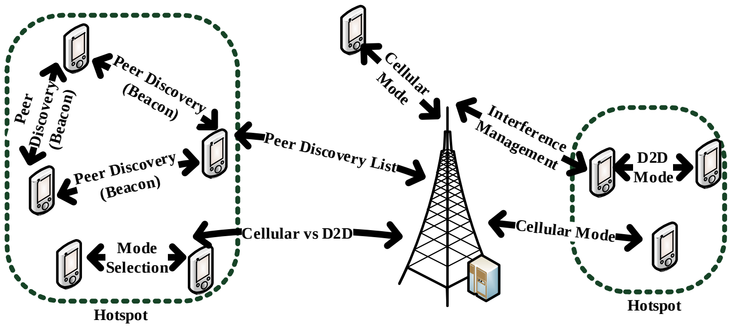


Figure 1.2: RRM procedures in D2D generic scenario.

Peer discovery in cellular networks has been studied in [30], where the authors propose a synchronous device discovery solution for networks based on the observations of the time synchronization. The results indicated that the solution has a large advantage over WiFi for device discovery, both in terms of range and energy efficiency. In [9], the authors focus on peer discovery for D2D communication in LTE networks. A new distributed discovery protocol is proposed for UEs to broadcast their presence. In the proposed protocol, UEs transmit beacons periodically to advertise their presence. The purpose of such control is for an eNB to minimize the required Resource Blocks (RBs) for beacon transmission, while still providing efficient peer discovery for D2D UEs. The authors concluded that the algorithm provides a good performance in discovery of UEs with mobility in LTE networks.

Regarding the resource assignment between cellular and D2D users, in [31], a heuristic algorithm considering channel gain information appropriately selects the shared radio resources for both users. In [32], the authors use the diversity in the cellular network to improve the network capacity. In [33], the system spectral efficiency is increased by allowing D2D users to reuse the resources of more than one cellular user in a system where perfect CSI is assumed.

Mode selection has been studied in [34–36]. In [34] semi-analytical studies have shown that when D2D communications share the same resources as the cellular network, significant gains in total throughput can be achieved compared to the conventional case, namely by the jointly and optimal allocation. However, numerical analyses have also shown that mode selection algorithms need to be designed carefully in order to prevent deteriorating the whole system performance. In [35], the authors derive equations that capture the network information such as link gains, noise levels, and Signal to Interference-plus-Noise Ratios (SINRs). The results shown that the main factors affecting the performance gain of D2D communication are the local communication probability and maximum distance between communicating nodes, as well as the mode selection algorithm. In [36], the eNB can decide whether the underlaying D2D pair should reuse cellular resources, get dedicated resources or communicate via eNB. One conclusion drawn from this paper is that an optimal communication mode selection strategy does not only depend on the quality of the link between D2D terminals and the quality of the link towards the eNB, but also on the interference situation.

PC schemes are one of keys to the harmonious coexistence between cellular and D2D communications. In this context, the transmit power of both communications need to be adjusted by the eNB based on channel gain, QoS demands, coverage and/or target SINR.

A PC method for D2D communications was proposed in [37] to maximize the network sum rate. Its optimality is discussed under practical constraints such as minimum and maximum spectral efficiency, and maximum transmit power. In [38], a power minimization solution with joint subcarrier allocation, adaptive modulation, and mode selection was proposed to guarantee the QoS demand of D2D and cellular communications. A simple PC scheme was proposed in [39] to regulate the transmit power of D2D-capable UEs and protect the existing cellular links in a single-cell scenario and deterministic network model. The algorithm imposes constraints on the SINR to allow quality degradation of cellular links until fixed levels are reached in DL and UL communication phases.

Different UL PC schemes have been studied for D2D communications in the literature [40, 41], including fixed transmit power schemes, fixed target Signal to Noise Ratio (SNR) schemes, and LTE PC schemes – Open Loop Power Control (OLPC) and Closed Loop Power Control (CLPC). In [40], a new PC scheme with double thresholding that coordinates the transmit power of D2D and cellular UEs to maximize the cell throughput and guarantee QoS levels is proposed in a scenario composed of a cellular UE and a D2D pair. The results show a throughput improvement in comparison with LTE OLPC. In [41], the authors use the LTE OLPC for cellular links and study other PC schemes for D2D links. The authors conclude that the LTE PC schemes gets close (especially for the conventional cellular UEs) in terms of transmit power and SINR levels to an optimization-based approach aiming to increase spectrum usage efficiency and to reduce sum power consumption.

In [42], the Soft Dropping Power Control (SDPC) scheme adjusts the transmit power to meet a variable target SINR in an UL single-carrier system. In [43], the SDPC scheme was used to protect cellular and D2D communications from mutual interference in a DL Orthogonal Frequency Division Multiple Access (OFDMA) system. It improved the spectral efficiency of cellular UEs in $14\,\%$ and still significantly reduced the power of D2D transmitters in $49\,\%$ without harming the spectral efficiency achieved by D2D receivers. Thus, the SDPC scheme appears as a promising solution to protect cellular UEs from the interference caused by D2D communications.

In [44], the authors examine the consequence of antenna downtilt and UL PC on the system level performance considering a realistic multicell 3D channel model. A highlight of the paper is the performance evaluation considering different downtilt angles and OLPC. The paper shows that angles between $4°$ and $8°$ are good for cells with radius in the range of $300\,\mathrm{m}$ based on a urban-macro path loss model based on the WINNER II [45] channel model.

A study about the relation between load balancing and antenna tilt adjustment schemes is one of the main contributions in [46]. The authors simulated different load balancing methods based on combinations of cell association algorithms and antenna tilt. The potential gain of traffic load balancing in terms of cell edge user throughput and significant cell edge user throughput improvements were observed by the authors, in contrast to the fixed case. In [47], antenna tilt adaptation was used to redistribute cell load from high congested areas to the areas with less congestion by using the Simulated Annealing [48] meta-heuristic and lead to efficient utilization of radio resources.

A research in field trial is detailed in [49]. The paper presents a set of UE locations, where downtilt could increase Signal to Interference Ratio (SIR) by about $5\,\mathrm{dB}$ to $10\,\mathrm{dB}$. Furthermore, the effect of downtilt on the multi-path channel, location of the user and the eNB power is investigated.

Strategies that exploit system-level analyses for the performance gains achieved with Radio Resource Allocation (RRA) strategies for rate maximization in downlink multi-antenna Coordinated Multi-Point (CoMP) systems are investigated in [50]. The authors realized analysis of the antenna downtilt to mitigate inter-cell interference and concluded that spatial diversity-based transmission schemes combined with downtilt provided satisfactory gains, especially for low loads expressed in number of active UEs per cell. In [51], antenna tilt adaptation is used for capacity optimization using techniques to identify the dominant interfering cells. Results show that the proposed technique identifies a reduced set of potentially significant interfering cells among the neighbors which have considerable impact on system performance.

In order to present basic effects on network coverage and capacity due to changes in the antenna downtilt angle configuration when mechanical or electrical adjustment of the downtilt is used, the paper [52] shows the percentage of covered area under certain circumstances. The electrical adjustment of the downtilt angle performed slightly better than the mechanical one. According to the results presented therein, the smaller the cell size the larger the antenna downtilt should be; and the higher the traffic load per cell the smaller the antenna downtilt should be. In [53], the potential gain of tilt optimization due to user traffic distribution is investigated for the 3rd Generation Partnership Project (3GPP) urban propagation environment. Therein, a traffic hotspot situation is assumed, the tilt of each sector is adapted, and user throughput performance targets are defined. According to the authors, the performance gain is larger for higher traffic densities at the hotspot.

1.5 Thesis Organization and Contributions

This thesis is organized as follows. In Chapter 2, we concentrate on the methodology and system model that are applicable in cellular networks integrating D2D communications. More specifically, we show the RRM for cellular communications and discuss about mode selection, resource allocation, grouping and power control for D2D communications. The benefits of D2D communications underlaying cellular networks are detailed in different topics as security, performance and energy efficiency. Subsequently the details about physical radio resources, wireless channel, transmission, link-to-system interface and imperfect CSI modeling are addressed. Finally, we show the classification of metrics used to quantify energy efficiency at network, system and component levels.

In Chapter 3, we explain about the efficiency energy methods used to analyze the D2D scenarios addressed in Chapter 2. In this chapter we focus on baselines such as Equal Power Allocation (EPA), Fixed Power and Fixed SINR, which are used to compare the efficiency of Open Loop Power Control (OLPC), Closed Loop Power Control (CLPC), Soft Dropping Power Control (SDPC) and Closed Loop Soft Dropping (CLSD). Next, we describe the formulation of a simple and efficient downtilting, which is used to reduce undesired effects as inter- and intra-cell interference.

In Chapter 4, we show the results of the performance evaluation of the referred PC schemes in a macro-cell and in a micro-cell scenario using UL or DL bands. The main contributions are:

- Show the performance of PC with variable target SINR levels in a multi-cell scenario,
- Compare the LTE PC schemes,
- Suggest and analyze the parameters for the CLPC scheme,
- Show the performance of PC with variable target SINR levels in a multi-cell scenario,
- Show the minimum performance impact on cellular communications for enabling D2D gains in a multi-cell scenario,
- Propose an SDPC-like alternative as PC scheme,

- Calibrate operating points of the considered PC schemes for energy efficiency of cellular and D2D communications,
- Create and analyze the performance of CLSD,
- Test the performance of PC for different loads,
- Examine the impact of imperfect CSI,
- Show the convergence of SDPC,
- Implement the downtilt in the OFDMA system with D2D communications underlying cellular networks,
- Show the impact of downtilt in a multi-cell scenario,
- Determine range of downtilt angles that impact positively on cellular and D2D communications.

In Chapter 5, we summarize the main conclusions obtained along the master's thesis. Furthermore, we point out the main research directions that can be considered as extension of the study performed in this master's thesis.

1.6 Scientific Production

The contents and contributions present in this thesis were published and submitted with the following information:

- **Melo, Y.V.L**; Batista, Rodrigo L.; Maciel, Tarcisio F.; Silva, Carlos F.M.e; da Silva, Jose Mairton B.; Cavalcanti, Francisco R.P., "Power control with variable target SINR for D2D communications underlying cellular networks," in European Wireless 2014 (EW2014), Barcelona, Spain, May 2014.
- **Melo, Y.V.L**; Batista, Rodrigo L.; Silva, Carlos F.M.e; Maciel, Tarcisio F.; da Silva, Jose Mairton B.; Cavalcanti, Francisco R.P., "Power Control Schemes for Energy Efficiency of Cellular and Device-and-Device Communications," in Wireless Communications and Networking Conference (WCNC), New Orleans, United State of America, March 2015.
- **Melo, Y.V.L**; Batista, Rodrigo L.; Silva, Carlos F.M.e; Maciel, Tarcisio F.; da Silva, Jose Mairton B.; Cavalcanti, Francisco R.P., "Uplink Power control with variable target SINR for D2D communications underlying cellular networks," in Vehicular Technology Conference (VTC2015-Spring), Glasgow, Scotland, May 2015.

In parallel to the work developed during the master's course, I have been working on other research projects, which are in the context of power allocation and grouping:

- **Melo, Y.V.L**; Rodrigues, E.B.; Lima, F.R.M.; Maciel, Tarcisio F.; Cavalcanti, Francisco R.P., "Evaluation of Utility-Based Adaptive Resource and Power Allocation for Real Time Services in OFDMA Systems," in International Telecommunications Symposium (ITS-2014), São Paulo, Brazil, August 2014.
- da Silva, Jose Mairton B.; Maciel, Tarcisio F.; C. F. M. e Silva, Batista, Rodrigo L. and **Melo, Y.V.L**, "User Equipment Grouping for Device-to-Device Communications Underlying a Multi-Cell Wireless System" in EURASIP Journal on Wireless Communications and Networking (submitted).

In the context of the same project, I have participated on the following technical reports:

- Silva, Carlos F.M.e; J. Mairton B. da Silva Jr.;**Melo, Y.V.L**; Maciel, Tarcisio F.; and Cavalcanti, Francisco R.P., "RRM and QoS Management for 5th Generation Wireless Systems", GTEL-UFC-Ericsson UFC.40, Tech. Rep., March. 2015, First Technical Report.
- Batista, Rodrigo L.; Silva, Carlos F.M.e; da Silva, Jose Mairton B.; **Melo, Y.V.L**; Maciel, Tarcisio F.; and Cavalcanti, Francisco R.P., "Network-Assisted Device-to-Device Communications", GTEL-UFC-Ericsson UFC.33, Tech. Rep., Aug. 2014, Fourth Technical Report.
- Batista, Rodrigo L.; Silva, Carlos F.M.e; da Silva, Jose Mairton B.; **Melo, Y.V.L**; Maciel, Tarcisio F.; and F. R. P. Cavalcanti, "Network-Assisted Device-to-Device Communications", GTEL-UFC-Ericsson UFC.33, Tech. Rep., Jan. 2014, Third Technical Report.
- Batista, Rodrigo L.; Silva, Carlos F.M.e; da Silva, Jose Mairton B.; **Melo, Y.V.L**; Maciel, Tarcisio F.; and Cavalcanti, Francisco R.P., "Network-Assisted Device-to-Device Communications", GTEL-UFC-Ericsson UFC.33, Tech. Rep., Aug. 2013, Second Technical Report.
- Rodrigues, E.B.; Lima, F.R.M.;**Melo, Y.V.L**; Costa Neto, Francisco Hugo; Maciel, Tarcisio F.; and Cavalcanti, Francisco R.P., "Analysis and Control of Trade-Offs Involving QoS Provision", GTEL-UFC-Ericsson UFC.33, Tech. Rep., Aug. 2013, Second Technical Report.
- Batista, Rodrigo L.; Silva, Carlos F.M.e; da Silva, Jose Mairton B.; **Melo, Y.V.L**; Maciel, Tarcisio F.; and Cavalcanti, Francisco R.P., "Network-Assisted Device-to-Device Communications", GTEL-UFC-Ericsson UFC.33, Tech. Rep., Feb. 2013, First Technical Report.

Chapter 2

Methodology and System Modeling

This chapter covers the fundamental issues about the methodology, system modeling and features of Device-to-Device (D2D) communications, so that a reader without prior knowledge could understand the problems and challenges in such systems. Terminology related to the scope of this master's thesis are presented in more detail. The remainder of this chapter report is structured as follows. In Sections 2.1 and 2.2 described basic features of wireless network and traditional Radio Resource Management (RRM) are presented. In the Sections 1.2 and 1.3, detailed aspects of D2D communication and RRM. In Sections 2.3, 2.4, 2.6 and 2.7 are detailed the system model. Finally, Sections 2.8, 2.9, 2.10 presents imperfect Channel State Information (CSI), simulation parameters and classification of metrics for energy efficiency.

2.1 Wireless System

The traditional standards of wireless communication can be classified in terms of coverage, as shown in Figure 2.1. Wireless Personal Area Network (WPAN) is used in personal networks (i.e. at small coverage) while Wireless Wide Area Network (WWAN) can cover several kilometers and provide service to thousands of users.

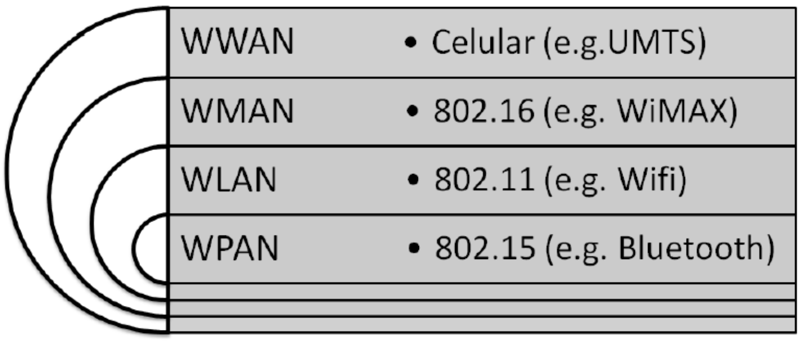


Figure 2.1: Classification of wireless communication networks according to the coverage.

After the success of the Global System for Mobile Communications (GSM), new researches have been conducted by academy and industry to improve general aspects as Quality of Experience (QoE), security and cost, in addition to specific aspects as spectral efficiency, power efficiency and new communication architectures.

The goals of the 3rd Generation (3G) of wireless communication systems were announced by International Telecommunication Union (ITU) and called International Mobile Telecommunications (IMT)-2000. By request of the ITU, several organizations joined the 3rd Generation Partnership Project (3GPP) and described its ideas for 3G networks. The outcome of the discussions was sent to ITU, which was responsible for the choice and documentation of the proposed system. The system approved as 3G should provide worldwide roaming, high transmissions rates (e.g. minimum of $2\,\mathrm{Mbit/s}$ to low mobility users and $348\,\mathrm{Kbit/s}$ to high mobility) [54].

2.2 Radio Resource Management

The goal of a communication company is to provide a capable network to keep the maximum amount of clients with a determined Quality of Service (QoS) level. To ensure a minimum QoS level is necessary to overcome several challenges (e.g. propagation, traffic and interference) present in the cellular communication environment. In order to ensure high data rate, coverage and satisfactory QoS it is fundamental to apply RRM, in other words, RRM is a set of techniques, which ensure system capacity while the requirements of coverage and QoS of the users are satisfied, overcoming difficulties inherent to radio propagation.

The traditional RRM techniques can be grouped into three categories: Power Control (PC), mobility control (handover) and congestion control. PC is very important in systems that employ frequency reuse, such as in Wideband Code Division Multiple Access (WCDMA). In this case, all users use the same frequency and, therefore, it is important to have an efficient interference control. Thus, PC chooses the lowest transmit power necessary to achieve a target QoS level, otherwise a user poorly managed (in terms of transmit power) can harm links of all users in system [55]. The mobility control is necessary when an user changes its location. The system must provide the switching of all radio resources from one cell to another, so that the user does not suffers any harm in his/her QoS [56].

The congestion control can be subdivided into admission control, load control and scheduling. In congestion control, admission control and load control work together to offer stability of QoS, coverage and capacity. There are strategies to block the access of new users or make handover to balance the load, while keeping the stability of the system. In others words, the admission control decides if a new connection must be established or not, while load control tries to keep active communications at an acceptable QoS level by interrupting (bad) connections in progress or performing handover. Finally, scheduling is responsible for exploring the physical resources available (e.g. time, frequency and code) in an effort to achieve fairness and capacity in the system [57].

2.3 Physical Resource

For Long Term Evolution (LTE), 3GPP specifies the Orthogonal Frequency Division Multiple Access (OFDMA) technology as radio access technique. OFDMA allows to exploit frequency and multiuser diversities, since different subcarriers present different fading if sufficiently apart and channel fading also varies for User Equipments (UEs) at different locations. Thus, one can allocate subcarriers to UEs depending on their channel fading state/channel quality. As it is well-known, OFDMA is based on Orthogonal Frequency Division Multiplexing (OFDM) and enables the transmission of multiple parallel low-rate data streams over orthogonal subcarriers, which correspond to narrow band channels created by sub-dividing the system bandwidth. It allows each UE to be assigned resources that are orthogonal in time and frequency. Usually, due to signaling constraints, subcarriers are not allocated individually, but in blocks of adjacent OFDM subcarriers, which represent the Physical Resource Blocks (PRBs) [58]. Channel coherence bandwidth is assumed larger than the bandwidth of a PRB leading to flat fading over each PRB. For a given PRB, the complex channel coefficients considered in this thesis correspond to those associated with the middle subcarrier of the considered PRBs. In 3GPP LTE, an OFDM frame structure takes the form of a frequency-time resource grid as shown in Figure 2.2.

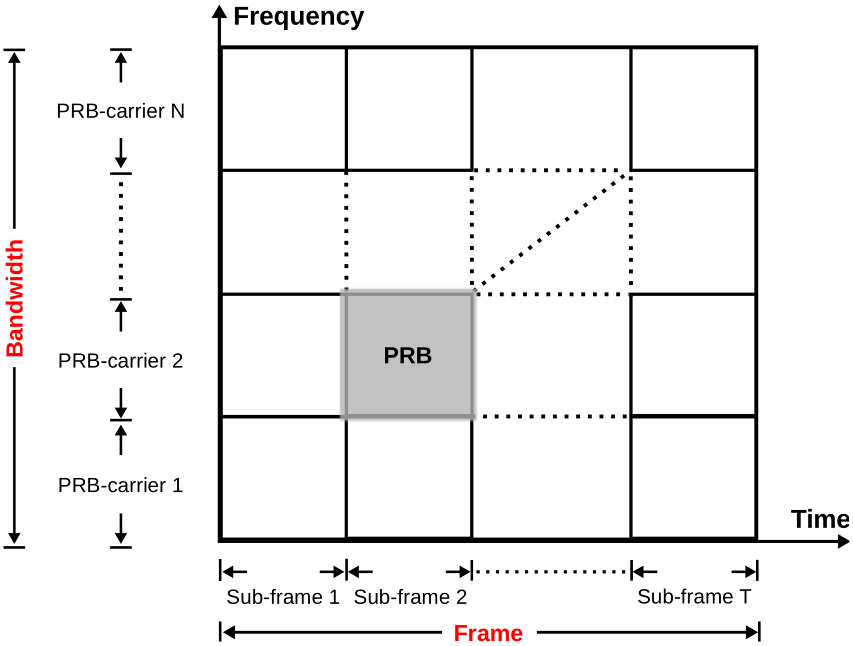


Figure 2.2: OFDMA frame structure.

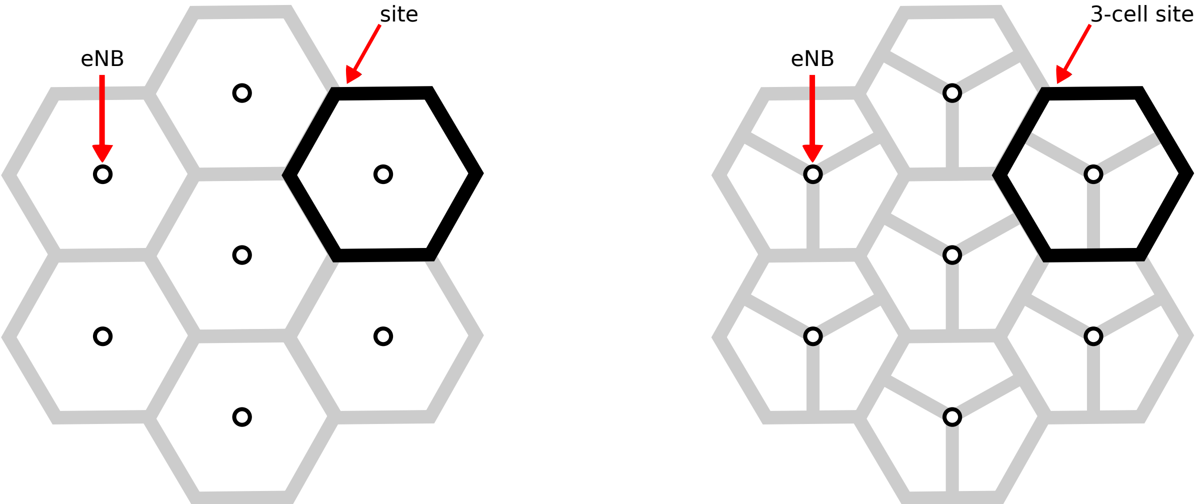
As it is seen in Figure 2.2, the bandwidth has N_{PRB} PRBs and the Transmission Time Intervals (TTIs) are grouped into frames, each composed of N_{SUBFRAME} subframes, where each subframe supports Downlink (DL) or Uplink (UL) links and takes the duration of one TTI. The PRB is defined as one subframe in the time domain, which is divided into 14 symbols, and 12 contiguous OFDM sub-carriers spaced of $15\,\text{kHz}$ in the frequency domain. The minimum allocable resource in LTE systems is the PRB. This unit corresponds to the available resource that can be assigned to UEs by an Radio Resource Allocation (RRA) function of the system.

2.4 Multi-cell Scenario

The multi-cell scenario considered in this master's thesis corresponds to a cellular network with Evolved Node Bs (eNBs) uniformly distributed over the coverage area. It was assumed that each eNB is placed at the center of a cell site, which is represented by a regular hexagon. Two 3GPP fading environments are considered: urban-microcell and macrocell [59]. Graphically, the multi-cell scenario is shown in Figure 2.3 for both 3GPP environments.

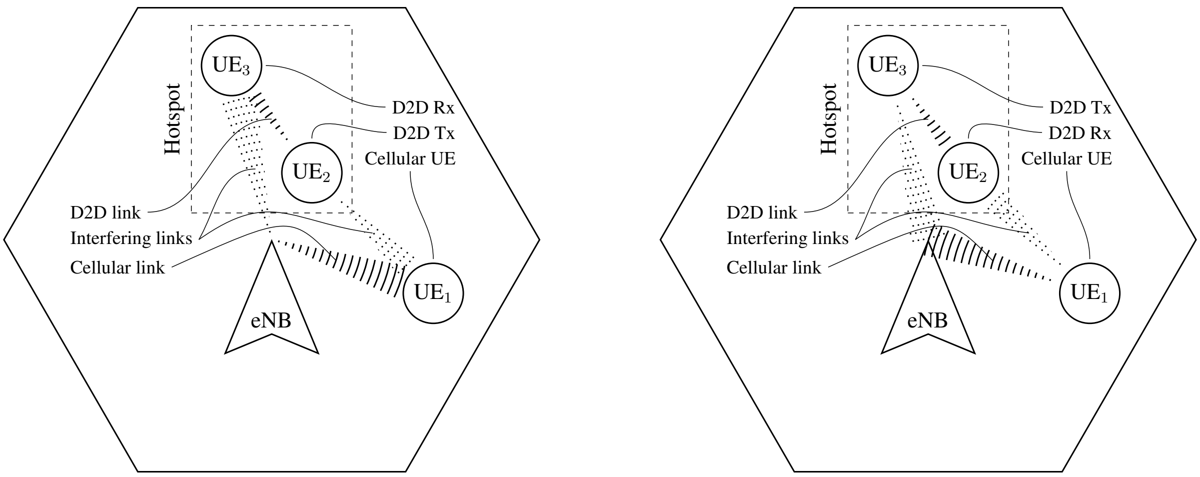
As depicted in Figure 2.3, in the urban-microcell environment the site comprises only a single cell while in the urban-macrocell environment it comprises three cells. In the considered notation, it is assumed that the multi-cell scenario is composed of N_{CELL} cells and serves a number N_{UE} of UEs uniformly distributed over its coverage area. Each UE is equipped with $N_{\text{UE-ANT}}$ omnidirectional antennas.

Each cell comprises a hotspot zone located near the cell-edge in order to model situations in which D2D communications are likely to happen [3]. Herein, $50\,\%$ of the total number of UEs within the cell are clustered inside a $50 \times 120\,\text{m}$ hotspot zone while the remaining UEs are uniformly distributed over the cell area. Considering that UEs inside the hotspot are close to each other and far from most cellular UEs, pairs of D2D-capable UEs are obtained by a simply random pairing procedure [3]. Figures 2.4(a) and 2.4(b) exemplify cellular and D2D communications in such hotspot zones in the urban-microcell environment for the DL/UL communication phase



(a) Urban-microcell environment. **(b)** Urban-macrocell environment.

Figure 2.3: Coverage area of the multi-cell scenario.



(a) Cellular and D2D communication in DL. **(b)** Cellular and D2D communication in UL.

Figure 2.4: Communication within a cell for both directions(DL and UL), where the solid lines describe the interesting links and the dashed lines represent the interfering links.

Due to D2D communication, in both UL and DL communication phases both UEs and cells may be transmitters or receivers at the same TTI. Let $\mathcal{T}$ denote the transmitters set and $\mathcal{R}$ the receivers set. In a given communication phase, one can include the set of all cells, denoted by $\mathcal{C} = \{\text{CELL}_1, \text{CELL}_2, \ldots, \text{CELL}_{N_{\text{CELL}}}\}$, and/or the set of all UEs, denoted by $\mathcal{U} = \{\text{UE}_1, \text{UE}_2, \ldots, \text{UE}_{N_{\text{UE}}}\}$, in the multi-cell system. In Table 2.1, transmitter and receiver sets are summarized for both UL and DL communication phases.

Table 2.1: Transmitter and receiver sets for D2D communications in both UL and DL communication phases.

Parameter	**DL**	**UL**
Transmitters set ($\mathcal{T}$)	$\mathcal{C} \cup \mathcal{U}$	$\mathcal{U}$
Receivers set ($\mathcal{R}$)	$\mathcal{U}$	$\mathcal{C} \cup \mathcal{U}$
Number of transmitters (N_{TX})	$N_{\text{CELL}} + N_{\text{UE}}$	N_{UE}
Number of receivers (N_{RX})	N_{UE}	$N_{\text{CELL}} + N_{\text{UE}}$

It is assumed that frequency resources can be fully reused in all cells. Since the number of UEs is typically larger than the number of available resources, UEs have to be scheduled by the RRA algorithms. As shown in Figure 2.2, in each subframe there exist N_{PRB} PRBs in the system and each of them might be assigned to one or more UEs in each cell.

2.5 Wireless Channel Model

The modeling of the complex channel coefficients includes propagation effects on the wireless channel, namely, path loss, shadowing, short-term fading and also includes the antenna gains. The distance dependent Non-Line of Sight (NLOS) pathloss in the microcell environment is based on the COST 231 Walfish-Ikegami NLOS model, whereas the pathloss in the macrocell environment is based on the modified COST 231 Hata urban propagation model. Particular aspects of path loss modeling for both urban-macrocell and urban-microcell environments are described in [59]. Path loss model for macrocell and microcell environments are $34.5 + 35\log_{10}(\mathrm{d})$ and $35.7 + 38\log_{10}(\mathrm{d})$, respectively. Slow channel variations due to shadowing are modeled by a lognormal distribution of zero mean and standard deviation σ_{sh}. For D2D communications, while the large-scale shadowing is defined according to environment, the path loss model [60] employed for both environments is given by

$$PL(d) = 37 + 30\log_{10}(\mathrm{d}). \tag{2.1}$$

Concerning the small-scale fading, the Spatial Channel Model (SCM) is considered. SCM is a stochastic channel model developed by 3GPP for evaluating Multiple Input Multiple Output (MIMO) system performance and incorporates important parameters such as phases, delays, Doppler frequency, and ray angles [59]. The spatial characteristics of the SCM are described by scatterers and clusters of scatterers placed over the considered scenario. Details of relevant parameters for the SCM as well as their values are addressed in [59]. In this master's thesis, the SCM simulator available in [45][1] is used for obtaining the small-scale fading, which is in accordance with the SCM specified in [59].

2.6 Transmission Model

It is necessary to calculate the Signal to Interference-plus-Noise Ratio (SINR) in both UL and DL communication for each receiver in order to estimate data rates. When considering the transmissions on a single PRB of the multi-cell scenario, the cellular and D2D SINR are, respectively,

$$\gamma_{k,c,n}^{(t)CELLULAR} = \frac{\left|h_{k,c,n}^{(t)}\right|^2 p_{k,c,n}^{(t)}}{\underbrace{\sum_{c'\neq c}^{C}\sum_{k'}^{K}\left|h_{k,c',n}^{(t)}\right|^2 p_{k',c',n}^{(t)}}_{\text{Interference from cellular links}} + \underbrace{\sum_{c'}^{C}\sum_{m'}^{M}\left|h_{k,tx(m'),c',n}^{(t)}\right|^2 p_{rx(m'),tx(m'),c',n}^{(t)}}_{\text{Interference from D2D links}} + \eta^2}, \tag{2.2}$$

and

$$\gamma_{rx,c,n}^{(t)D2D} = \frac{\left|h_{rx(m),tx(m),c,n}^{(t)}\right|^2 p_{rx(m),tx(m),c,n}^{(t)}}{\underbrace{\sum_{c'}^{C}\sum_{k'}^{K}\left|h_{rx(m),c',n}^{(t)}\right|^2 p_{k',c',n}^{(t)}}_{\text{Interference from cellular links}} + \underbrace{\sum_{c'\neq c}^{C}\sum_{m'}^{M}\left|h_{rx(m),tx(m'),c',n}^{(t)}\right|^2 p_{rx(m'),t(m'),c',n}^{(t)}}_{\text{Interference from D2D links}} + \eta^2}, \tag{2.3}$$

where:

- k is the receiver in a cellular communication;
- c is the transmitter in a cellular communication;

[1]The code of the SCM simulator of [45] was developed in the Wireless World Initiative New Radio (WINNER) project. The software is licensed under the GNU General Public License (GPL).

- n is the PRB;
- t is the TTI;
- $h_{k,c,n}^{(t)}$ is the channel that models the link between the receiver k and the transmitter c in PRB n at TTI t;
- $p_{k,c,n}^{(t)}$ is the transmit power allocated to transmitter c to link between the receiver k in PRB n at TTI t;
- $tx(m)$ is the transmitter D2D pair $m \in \{0, 1, \ldots, R\}$;
- $rx(m)$ is the receiver D2D pair $m \in \{0, 1, \ldots, R\}$;
- $p_{rx(m),tx(m),c,n}^{(t)}$ is the transmit power allocated to transmitter pair $tx(m)$ to link between the receiver $rx(m)$ in PRB n at cell site c and TTI t;
- η^2 is the thermal noise power at the receiver.

2.7 Link-to-System Interface

In the following, the link-to-system interface is addressed, which is used to map the system-level metrics, such as SINR, into link-level performance figures, such as BLock Error Rate (BLER). The link adaptation selects a proper Modulation and Coding Scheme (MCS) for each link in order to maximize the throughput for each transmission based on effective gains achieved by the RRA algorithm [61]. For the sake of simplicity, the MCS for each PRB of a UE are adapted independently.

Aligned with LTE, a set of fifteen MCSs based on Quadrature Amplitude Modulation (QAM) and different code rates are available for link adaptation [62]. Figure 2.5 shows the average throughput curves available for link adaptation, from MCS-1 (leftmost) to MCS-15 (rightmost).

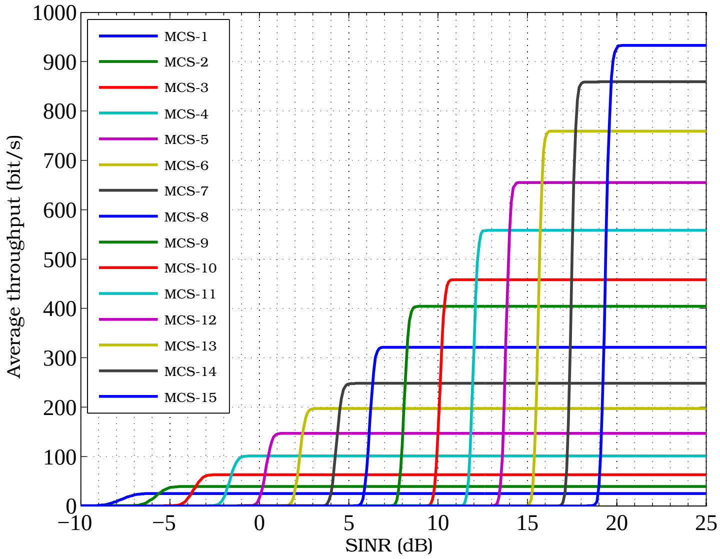


Figure 2.5: Curves of link-level used for link adaptation.

In each transmission, the link adaptation is determined such that the MCS that yields the maximum average throughput is selected. SINR thresholds can be found for each MCS, i.e., minimal SINR values required to use each MCS. The MCSs considered in this master's thesis and its respective SINR thresholds are summarized in Table 2.2.

It should be noted that the link adaptation can be affected by random variations on the interference levels in the system. We consider that rates are computed considering ideal link

Table 2.2: SINR thresholds for link adaptation [62].

MCS	**Modulation**	**Code rate** [$\times 1024$]	**Rate** [Bits/symbol]	**SINR threshold** [dB]
MCS-1	QPSK	78	0.1523	−6.2
MCS-2	QPSK	120	0.2344	−5.6
MCS-3	QPSK	193	0.3770	−3.5
MCS-4	QPSK	308	0.6016	−1.5
MCS-5	QPSK	449	0.8770	0.5
MCS-6	QPSK	602	1.1758	2.5
MCS-7	16-QAM	378	1.4766	4.6
MCS-8	16-QAM	490	1.9141	6.4
MCS-9	16-QAM	616	2.4062	8.3
MCS-10	64-QAM	466	2.7305	10.4
MCS-11	64-QAM	567	3.3223	12.2
MCS-12	64-QAM	666	3.9023	14.1
MCS-13	64-QAM	772	4.5234	15.9
MCS-14	64-QAM	873	5.1152	17.7
MCS-15	64-QAM	948	5.5547	19.7

adaptation following the link level results from Figure 2.5 and that the communications occur error-free, i.e., there is no packet reception errors and all transmitted data are successfully received.

2.8 Imperfect Channel State Information

In this master's thesis, the imperfect CSI issue is addressed in order to illustrate conditions closer to real-world implementations. The CSI is reported to the transmitter via feedback channel in which delays can occur, this delay has a negative impact in the system, because the CSI values are outdated. For example, PC schemes are responsible for mitigating interference based on channel gain or SINR and when these values do not show the current situation of the scenario, the system is harmed due to too high or too low transmit power usage.

For the sake of simplicity, it is assumed that all UEs in the system experience the same delay, which is denoted by an integer number Δ_τ of TTIs. Finally, the outdated CSI is given in Δ_τ TTIs, i.e. $h_{k,c,n}^{(t)} = h_{k,c,n}^{(t+\Delta_\tau)}$. This is the CSI effectively used as CSI. Figure 2.6 shows two cases, the first case has $\Delta_\tau = 0$ (perfect CSI), and the second case has $\Delta_\tau = 2$ (imperfect CSI). In the first TTI of the simulations all values are available to computer CSI in both case.

In the first case, when $\Delta_\tau = 0$ the PC schemes determine transmit power based on current TTI, because it does not have delay. In the second case, when $\Delta_\tau = 2$ the PC schemes determine transmit power based on the CSI of a past TTI. For example, the CSI of the 2nd and 3th TTI are based on the CSI of the 1st TTI, while the CSI of the 5th and 6th TTI are based on the CSI of the 4th TTI, and so on.

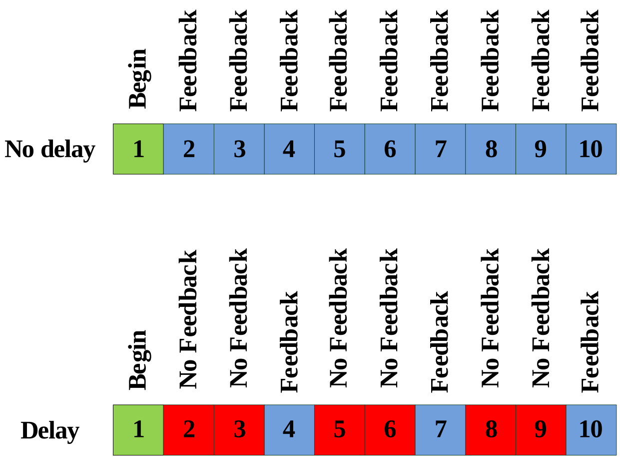


Figure 2.6: Imperfect CSI using feedback delay.

2.9 System Level Simulation

Computer simulation is taken as an important tool to analyze and assess the performance of complex systems such as D2D links. Thus, a system-level simulation tool based on the system model described in this chapter has been implemented. The main parameters considered in the simulations are summarized in Table 2.3.

Table 2.3: Simulation parameters for urban-macrocell and microcell environments.

Parameters	Urban-macrocell	Urban-microcell	Unit
Cellular scenario			
Number of eNBs	7	7	-
Inter-site distance	3 000	500	m
eNB height	32	12.5	m
UE height	1.5	1.5	m
CSI knowledge	Perfect	Perfect / Imperfect	-
Link adaptation	LTE (15 MCSs)	LTE (15 MCSs)	[63]
Interference margin	Last interference	Last interference	[3]
eNB transmit power	48	38	dBm [64]
UE transmit power	24	24	dBm [64]
Thermal noise power	-112.4	-112.4	dBm [64]
SINR threshold for lowest MCS	-6.2	-6.2	dB [65]
Average user speed	3	3	km/h [64]
OFDMA			
Central carrier frequency	1.9	1.9	GHz [66]
System bandwidth	5	5	MHz
Number of PRB	25	25	
Number of symbols per TTI	14	14	
Propagation			
Path loss model for cellular links	$34.5 + 35\log_{10}(d)$	$35.7 + 38\log_{10}(\mathrm{d})$	dB
Path loss model for D2D links	$37 + 30\log_{10}(d)$	$37 + 30\log_{10}(d)$	dB
Lognormal shadowing std. deviation	8	10	dB
Fast fading model	3GPP SCM	3GPP SCM	[66]
Simulation			
Traffic model	Full buffer	Full buffer	
Number of UEs per cell	4	4,8,16,32	
Snapshot duration	1 s	1 s	

2.10 Classification of Metrics Used in Energy Efficiency

We need to understand some metrics used in this master's thesis, which allow for the comparison of different algorithms. According to [2], energy efficiency metrics are used to describe the ability of a telecommunication system to minimize energy waste. For instance, when a telecommunication system transmits more data (bits) with less power (Watt), this system is considered more energy efficient. An energy efficiency metric can be defined at the network level, the system level and the component level. In Table 2.4 are summarized the main metrics to energy efficiency.

2.10.1 Energy Efficiency at the Network Level

Network level metrics are used to evaluate the energy efficiency of an entire network or part of it. Network level metrics assess energy efficiency at the network level by considering the features and properties of the capacity and coverage of the network. In other words, it is normally used to evaluate a network for internal operator use or to satisfy an environmental assessment. So, the network level is considered a metric that will cover not only one equipment, but also a telecommunication network composed of different interworking equipments.

2.10.2 Energy Efficiency at the System Level

System level metrics are related with access node, which is used to compare and analyze RRM algorithms that approach resource allocation, power control, interference coordination and cooperative scheduling. Important system level metrics used in this master's thesis are summarized bellow:

- **Spectral efficiency** is a metric that considers the amount of information tha can be transmitted per bandwidth unit. Spectral efficiency is directly related with system capacity, therefore, it is possible to compare capacity of two or more algorithms in a system providing the same service by using it. In this master's thesis spectral efficiency is expressed in [bps/Hz/cell];

- **Power efficiency** is a essential metric, which can be modified according to RRM algorithms, load, and environmental factors. Power efficiency can be describe as spectral efficiency per unit of power, i.e., [bps/Hz/cell/W].

2.10.3 Energy Efficiency at the Component Level

Component level metrics can be used in the design, development and manufacture of energy efficient devices. Component level metrics are useful to compare the hardware of a communication device, such as Central Processing Unit (CPU), memory, power source, Large-Scale Integration (LSI) microfabrication and power amplifier. Measuring and understanding the energy efficiency or energy consumption of each component within the equipment helps to identify key components in a system with regard to energy saving.

Table 2.4: Metrics Used in Energy Efficiency.

Level	Units	Description
Component Level	W/Gbps	The ratio of energy consumption to effective system capacity
	Gbps/W	The ratio of useful work to power consumption
	MIPS/W	Millions of instructions per second per Watt
	MFLOPS/W	Millions of floating-point operations per second per watt
System Level	b/s/Hz	Rate of information can be transmitted in a bandwidth
	b/s/Hz/W	The spectral efficiency per Watt
	(b·m)/s/Hz/W	Rate of transmission and the transmission distance attainable for a given bandwidth and power resources supplied
	J/bit	Number of bits transmitted per Joule of energy
Network Level	km^2/W	The ratio of coverage area to site power consumption
	W/km^2	The power consumed per unit area
	Users/W	The ratio of users served during the peak traffic hour
	J/bit/m^2	Number of transferred bits and the coverage area
	W/bps/m^2	The average power usage with respect to the average transmission rate and the coverage area

Chapter 3

Energy Efficiency RRM Methods

This chapter covers the Power Control (PC) schemes and downtilt used in this master's thesis, so that a reader can understand the principle of Equal Power Allocation (EPA), Fixed Power, Open Loop Power Control (OLPC), Closed Loop Power Control (CLPC), Soft Dropping Power Control (SDPC), Closed Loop Soft Dropping (CLSD) and downtit. The remainder of this chapter is structured as follows. In Section 3.1.1 is described the baselines EPA and Fixed Power. Next, in the Sections 3.1.2, 3.1.3 and 3.1.4 are detailed LTE PC schemes, SDPC and CLSD, respectively. Finally, in Section 3.2 downtilt is described.

3.1 PC

In this section, the PC schemes applied in this master's thesis are described. The baseline algorithms are the EPA and the Fixed Power. These algorithms have important function in this master's thesis, because they are the reference to the other PC schemes studied in this master's thesis.

3.1.1 EPA and Fixed Power

EPA is characterized by the equal distribution of the total transmit power P_{eNB} or P_{UE} among the Physical Resource Block (PRB). In other words, the EPA scheme obtains the power $p_{k,n}$ for each User Equipment (UE) k at PRB n as

$$P_{k,n} = \begin{cases} P_{\text{eNB}}/N_{\text{PRB}}, & \text{for eNB transmitters,} \\ P_{\text{UE}}/N_k, & \text{for UE transmitters.} \end{cases} \tag{3.1}$$

where N_k is the number of PRBs scheduled to the UE. Fixed Power is a simple PC scheme, where $p_{k,n} = P_{\text{UE}}/N_{\text{PRB}} = 10\,\text{dBm}, \forall k, n$.

3.1.2 LTE Power Control

The OLPC and CLPC are the standard LTE power control algorithms which work with fractional path loss compensation [63]. For this algorithm, the total transmit power p_k of a cellular or D2D UE k is given as

$$p_k = \min\{P_{\text{UE}}, P_0 - \alpha G + 10\log_{10} N_k + \triangle\}, \tag{3.2}$$

where P_{UE} is the maximum UE power, $0 \leq \alpha \leq 1$ is the pathloss compensation factor, G denotes the path gain of the channel, N_k is the number of PRBs scheduled to UE k and $\triangle$ is a dynamic offset. This dynamic offset differentiates OLPC from CLPC, because OLPC does not have feedback and, therefore, $\triangle = 0$, while CLPC has a feedback which can be computed as

$$\triangle = \begin{cases} (\Gamma_k - \gamma_k)\sigma, & if\ (\Gamma_k - \gamma_k)\sigma\ > 1, \\ 1, & if\ (\Gamma_k - \gamma_k)\sigma\ < 1. \end{cases} \tag{3.3}$$

where $0 < \sigma \leq 1$ is the dynamic offset compensation factor. P_0 is power level used to control the target SNR Γ_k, which is given according to [67] as

$$P_0 = \alpha(\Gamma_k + P_{\mathrm{N}}) + (1 - \alpha)(P_{\mathrm{UE}} - 10\log_{10} N_k), \tag{3.4}$$

where, for simplicity, P_{N} is the thermal noise power at the cellular or D2D receiver, respectively, eNB or UE. After total transmit power is updated, the power $p_{k,n}$ in each PRB n according to the EPA scheme as

$$p_{k,n} = p_k/N_k. \tag{3.5}$$

3.1.3 Soft Dropping Power Control (SDPC)

Power Control (PC) with variable SINR is an alternative approach to protect cellular and D2D communications from mutual interference. This approach, in which the target Signal to Interference-plus-Noise Ratio (SINR) gradually decreases as the required transmit power rises, it is called Soft Dropping (SD) in [42, 68–70]. It increases the probability of configuring a feasible PC problem — in which the target SINR values of all co-channel links can be reached — since links with worse quality, which demand higher power, aim at lower SINR values while links with better quality, which demand lower power, aim at higher SINR values.

The principle of the SD algorithm is illustrated in the Figure 3.1.

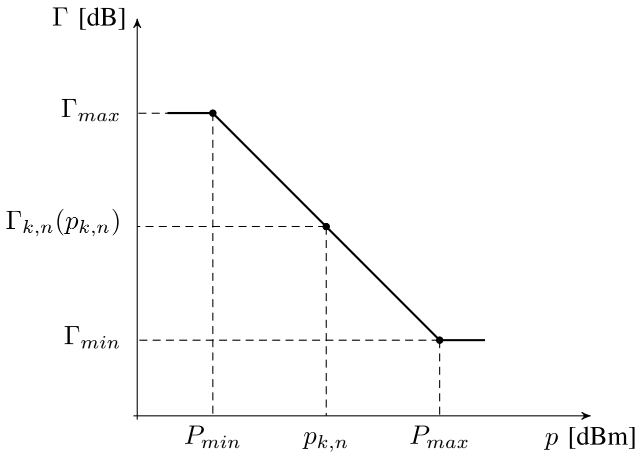


Figure 3.1: Target SINR as function of a variable transmit power.

In the SDPC scheme, the transmit power per PRB of each link is iteratively adjusted in order to find a power vector $\mathbf{p}$ for all UEs in the system such that the SINR $\gamma_{k,n}$ of each UE k in PRB n satisfies

$$\gamma_{k,n}(\mathbf{p}) \geq \Gamma_{k,n}(p_{k,n}), \tag{3.6}$$

where $\Gamma_{k,n}(p_{k,n})$ is the target SINR of the UE k in the PRB n, which varies according to the required transmit power $p_{k,n}$.

The SDPC scheme uses a target SINR varying from a maximum value Γ_{max} to a minimum Γ_{min} as the required transmit power goes from a minimum value P_{min} to a maximum P_{max}. Here, the range $\Delta_P = P_{max} - P_{min}$ is termed the PC range. For $p_{k,n} \leq P_{min}$, one attempts to maintain a high quality connection by aiming at a target SINR Γ_{max}. For $p_{k,n} \geq P_{max}$, one aims at a target SINR Γ_{min} which is relatively easier to reach when channel conditions are bad. Finally, for $P_{min} < p_{k,n} < P_{max}$, one aims for a target SINR $\Gamma_{k,n}(p_{k,n})$ that linearly (in logarithmic scale) trades SINR for transmit power. The target SINR $\Gamma_{k,n}(p_{k,n}^{(t)})$ of UE k in the PRB n at Transmission Time Interval (TTI) t is given according to

$$\Gamma_{k,n}(p_{k,n}^{(t)}) = \begin{cases} \Gamma_{max}, & p_{k,n}^{(t)} \leq P_{min}, \\ \Gamma_{max}\left(\frac{p_{k,n}^{(t)}}{P_{min}}\right)^{\rho}, & P_{min} < p_{k,n}^{(t)} < P_{max}, \\ \Gamma_{min}, & p_{k,n}^{(t)} \geq P_{max}, \end{cases} \tag{3.7}$$

where

$$\rho = \frac{\log_{10}(\Gamma_{min}/\Gamma_{max})}{\log_{10}(P_{max}/P_{min})}. \tag{3.8}$$

Then, the power per PRB of each UE is updated every transmission as follows

$$p_{k,n}^{(t+1)} = p_{k,n}^{(t)}\left(\frac{\Gamma_{k,n}(p_{k,n}^{(t)})}{\gamma_{k,n}(\mathbf{p}^{(t)})}\right)^{\beta}, \tag{3.9}$$

where β is a control parameter given by $(1-\rho)^{-1}$ [68].

Finally, whenever the achieved power $p_{k,n}^{(t+1)}$ is over P_{max} or under P_{min}, it is constrained as follows

$$p_{k,n}^{(t+1)} = \min\{P_{max}, \max\{p_{k,n}^{(t+1)}, P_{min}\}\}. \tag{3.10}$$

In this master's thesis, the maximum power P_{max} is exactly the power that would be obtained in each resource by employing EPA among the total number of resources as follows [43]:

$$P_{max} = \begin{cases} P_{\text{eNB}}/N_{\text{PRB}}, & \text{for eNB transmitters,} \\ P_{\text{UE}}/N_{\text{PRB}}, & \text{for UE transmitters.} \end{cases} \tag{3.11}$$

3.1.4 Closed Loop Soft Dropping (CLSD)

The CLSD is a hybrid PC scheme, because it uses features of CLPC and SDPC. The total transmit power $p_{k,n}$ of each cellular or D2D UE k in PRB n at TTI t is given according to

$$p_{k,n}^{(t+1)} = \min\{P_{\text{UE}}, P_0 - \alpha G + 10\log_{10} N_k + \triangle\}, \tag{3.12}$$

where P_{UE} is the maximum UE power, $0 \leq \alpha \leq 1$ is the pathloss compensation factor, G denotes the path gain of the channel, N_k is the number of PRBs scheduled to the UE k, and P_0 is power level used to control the target SINR $\Gamma_{k,n}(p_{k,n}^{(t)})$, which is given as

$$P_0 = \alpha(\Gamma_{k,n}(p_{k,n}^{(t)}) + P_{\text{N}}) + (1-\alpha)(P_{\text{UE}} - 10\log_{10} N_k), \tag{3.13}$$

where, for simplicity, P_{N} is the thermal noise power at the cellular or D2D receiver, respectively, Evolved Node B (eNB) or UE and $\triangle$ is a dynamic offset, which can be written as

$$\triangle = \begin{cases} \left(\Gamma_{k,n}(p_{k,n}^{(t)}) - \gamma_{k,n}(\mathbf{p}^{(t)})\right)\beta, & \text{if } \left(\Gamma_{k,n}(p_{k,n}^{(t)}) - \gamma_{k,n}(\mathbf{p}^{(t)})\right)\beta > 1, \\ 1, & \text{if } \left(\Gamma_{k,n}(p_{k,n}^{(t)}) - \gamma_{k,n}(\mathbf{p}^{(t)})\right)\beta < 1. \end{cases} \tag{3.14}$$

where $0 \leq \beta \leq 1$ is the dynamic offset compensation factor. The target SINR $\Gamma_{k,n}(p_{k,n}^{(t)})$ of UE k in the PRB n at TTI t and ρ are given according Equations (3.7) and (3.8), respectively.

In this master's thesis, the maximum power P_{max} is given according

$$P_{max} = P_{\text{UE}}/N_{\text{PRB}} \tag{3.15}$$

3.2 Downtilt

Currently, wireless systems face several issues that must be considered in its development and optimization. We can mention co-channel interference, irregular geographical terrain and improper antenna position as some factors that can have a negative impact on the network performance.

One simple and efficient method to reduce some of these negative effects is called downtilt. This method is used to adjust the coverage radius of an eNB and reduce co-channel interference by increasing cell isolation. There exist many different downtilt schemes, for example, mechanical tilt, electrical tilt, Variable Electrical Tilt (VET) and Remote Electrical Tilt (RET), which can be used to adjust coverage area, cell load, improve system capacity and traffic distribution.

In [71], the authors show important concepts about downtilting and the relationship between antenna height, downtilt angle, and coverage radius. The study outcomes that due to the severe urban propagation environments, the coverage area control by antenna downtilt has been reduced due to the high rise of tall buildings.

In [72], the authors discuss the impact of the Base Station (BS) mechanical antenna downtilt scheme on the downlink capacity of a 6-sectored Wideband Code Division Multiple Access (WCDMA) cellular network considering a macro-cellular environment. They conclude that an optimum mechanical downtilt angle exists in all simulation scenarios, and clearly this angle can be defined for each site and antenna configuration separately, depending on the BS antenna height and vertical beamwidth together with the site spacing. In relation to capacity, the downlink capacity increases with the downtilt angle but the coverage is reduced.

3.2.1 Antenna Fundamentals

Antenna is a device used for converting electromagnetic radiation in space into electrical currents in conductors or vice-versa, depending on whether it is being used for reception or for transmission, respectively. The pattern in which the radiating wave travels in the free space can be controlled by using different antenna parameters. The main parameters used in this master's thesis are antenna azimuth orientation and antenna downtilt. These antenna parameters that define the radiation pattern are explained below:

- **Antenna azimuth orientation** is the direction of the main lobe in the horizontal direction with positive values for the clockwise measurements from the horizontal axis.
- **Antenna downtilt** is the direction of the main lobe in the vertical direction with positive values for the down side tilting of the main lobe. The downtilt of the antenna radiation pattern can be done either by mechanical downtilt or by electrical downtilt. In case of mechanical downtilt, with changes in the downtilt values, there will be a variation in the horizontal radiation pattern of the antenna. In electrical downtilt, only vertical antenna radiation pattern is affected. In this master's thesis, the terms downtilt and electrical downtilt are used interchangeably.

This concept can be easier understood in Figure 3.2, which shows a macrocell scenario with eNB in center and 6 UEs. Each cell site have an azimuth orientation, which are $60°$, 180°and 300°. Another parameter in this scenario is the antenna downtilt, with each cell site having 20°downtilt angle with respect to the horizontal direction.

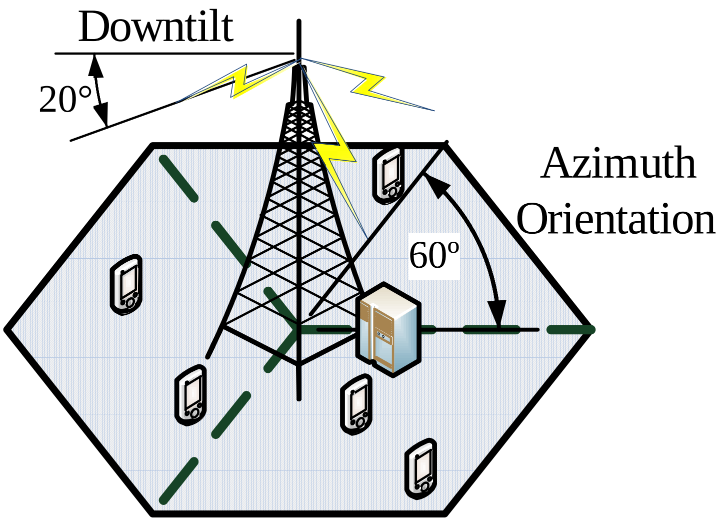


Figure 3.2: Azimuth orientation and downtilt in a macrocell scenario.

3.2.2 Electrical Antenna Downtilt

In this master's thesis, electrical downtilt is used, which has some differences compared to mechanical downtilt. The mechanical downtilt uses specific accessories, which are responsible for modifying the antenna bracket, while electrical downtilt changes the phase of the input signal and consequently the signal propagation directions. Each technique has clear differences in antenna radiation. The coverage is reduced in central direction with mechanical downtilt. However, the coverage in side directions is increased. When electrical downtilt is used, the coverage has an uniform reduction in the direction of the antenna azimuth orientation and the gain is reduced uniformly.

Antenna models were created to analyze electrical and mechanical downtilt in cellular networks. In [66], only horizontal radiation patterns were used. Nevertheless, several papers have described the improvement that can be achieved with the addition of the vertical pattern [44, 46, 47, 49]. In this master's thesis, a simple model for the vertical antenna pattern proposed in [73] is used, which is an extension of the 3rd Generation Partnership Project (3GPP) model. The horizontal model of antenna pattern in 3GPP [66] has a maximum gain G_m = 14 dB, front to back ratio FRB_h = 20 dB and a horizontal half power beamwidth $HPBW_h = 70°$. The horizontal antenna gain equation can be written as

$$G_h(\varphi) = -\min\{12(\varphi/HPBW_h)^2, FRB_h\} + G_m \tag{3.16}$$

where φ, $-180° \leq \varphi \leq 180°$, is the azimuth in degrees. It is possible to see that the model does not have antenna tilt, since it requires an antenna radiation pattern model defined over both horizontal and vertical directions. In [73], not only other parameter values for G_m = 18 dB, FRB_h = 30 dB and $HPBW_h = 65°$ are selected, but also the vertical pattern is defined as

$$G_v(\theta) = \max\{-12((\theta - \theta_{tilt})/HPBW_v)^2, SSL_v\} \tag{3.17}$$

where θ, $-90° \leq \theta \leq 90°$, is the angle relative to the horizontal plane. The others parameters are the electrical downtilt angle θ_{tilt}, side lobe level SSL_v = 18 dB and vertical half power beamwidth $HPBW_v = 6.2°$. These parameters are defined based on the Kathrein 742215 data sheet described in [73]. Through the combination of horizontal and vertical gain, it is possible to get the antenna gain in a general direction (φ, θ) as

$$G(\varphi, \theta) = G_h(\varphi) + G_v(\theta). \tag{3.18}$$

Chapter 4

Results and Analysis

This chapter covers the results of Power Control (PC) schemes and antenna downtilt used in this master's thesis for different scenarios. The remainder of this chapter is structured as follows. In Section 4.1.1 direction are presented and discussed the results to micro-cell scenario for Downlink (DL). In the Section 4.1.2 is detailed micro-cell scenario for Uplink (UL). Finally, in Section 4.2 the effect of antenna downtilt in a macro-cell scenario is discussed.

4.1 Power Control

To understand the behavior of PC schemes in a cellular network with underlaying Device-to-Device (D2D) communications, it is important to analyze both DL and UL scenarios, select PC schemes to cellular and D2D communications and adjust PC parameters based on spectral efficiency and power efficiency.

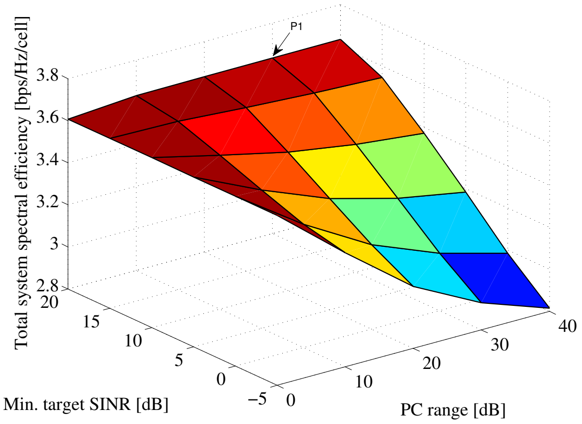
There are several parameters in PC schemes that need to be verified, modified and updated depending on the scenarios of interest. This section will present several scenarios, such as macro-cell or micro-cell scenarios with different number of users and using perfect or imperfect Channel State Information (CSI).

4.1.1 Power Control Evaluation in a Micro-cell Scenario (Downlink)

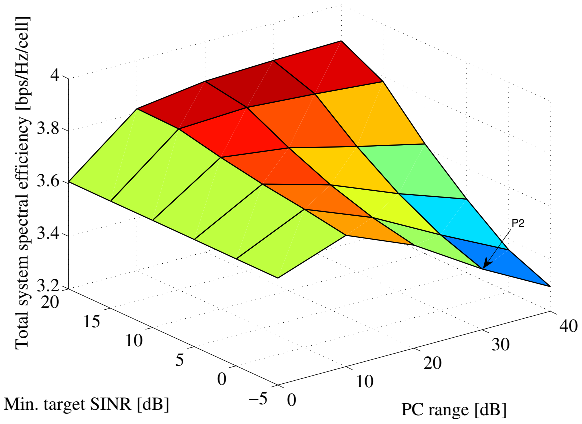
This section provides the performance assessment of a PC algorithm with variable Signal to Interference-plus-Noise Ratio (SINR) for cellular and D2D communications in a multi-cell scenario using DL direction. Results are obtained through system-level simulations aligned with 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) architecture [60, 63, 64, 66]. The main parameters considered in the simulations are summarized in Table 2.3, a load of 4 users are considered.

It is important to calibrate the Soft Dropping Power Control (SDPC), otherwise, the SDPC can harm the system. The results are compared with the baseline Equal Power Allocation (EPA).

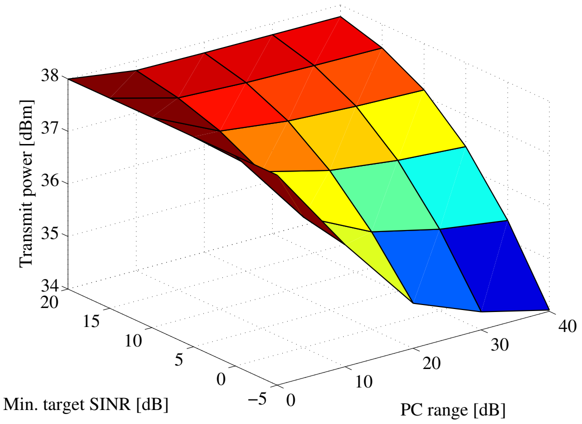
In the following, while the maximum target SINR is fixed in $\Gamma_{max} = 25\,\mathrm{dB}$, which is higher than the SINR threshold of the highest MCS [65], and the maximum power per Physical Resource Block (PRB) P_{max} is calculated by Equation (3.11), the PC range Δ_P and the minimum target SINR Γ_{min} are varied for calibration purposes. The simulated minimum SINR values Γ_{min} are above the SINR threshold of the lowest MCS [65] while the simulated minimum output power values P_{min} of a User Equipment (UE) do not go below $-40\,\mathrm{dBm}$ [74]. Figure 4.1 shows the total system spectral efficiency and the average transmit power achieved by the Soft Dropping (SD) algorithm for cellular and D2D communications.



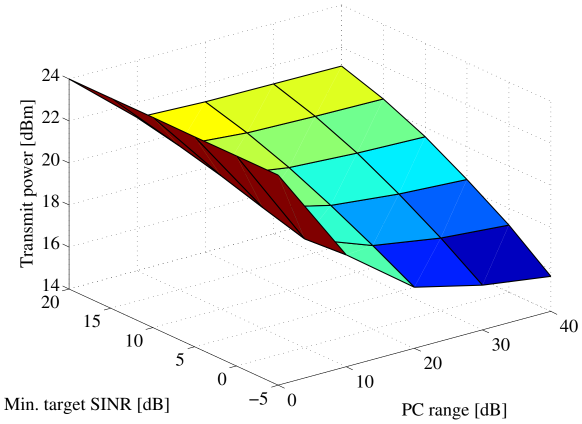
(a) Total system spectral efficiency achieved by cellular and D2D receivers (SD in cellular transmitters and EPA in D2D transmitters).



(b) Total system spectral efficiency achieved by cellular and D2D receivers (SD in D2D transmitters and EPA in cellular transmitters).



(c) Transmit power consumed by cellular transmitters (SD in cellular transmitters and EPA in D2D transmitters).



(d) Transmit power consumed by D2D transmitters (SD in D2D transmitters and EPA in cellular transmitters).

Figure 4.1: Calibration of SD algorithm regarding the total system spectral efficiency and transmit power.

As depicted in Figures 4.1(a) and 4.1(b), the highest total system spectral efficiency values are achieved for $\Gamma_{min} = 20\,\text{dB}$ while the lowest transmit power values are achieved for $\Gamma_{min} = -5\,\text{dB}$ in both cellular and D2D communication cases. Therefore, I consider two operation points: P_1 is set for evaluating system spectral efficiency gains, while P_2 is set for evaluating the power saving.

For $\Gamma_{min} = 20\,\text{dB}$, the gains in system spectral efficiency practically saturate for Δ_P greater than $30\,\text{dB}$, as also shown in Figures 4.1(a) and 4.1(b). Thus, P_1 is set as ($\Gamma_{min} = 20\,\text{dB}$, $\Delta_P = 30\,\text{dB}$).

Considering $5\,\%$ of reduction on the total system spectral efficiency achieved when applying SD to D2D communications, P_2 is set as ($\Gamma_{min} = -5\,\text{dB}$, $\Delta_P = 30\,\text{dB}$), hereafter P_1 and P_2 will be used for the remaining results.

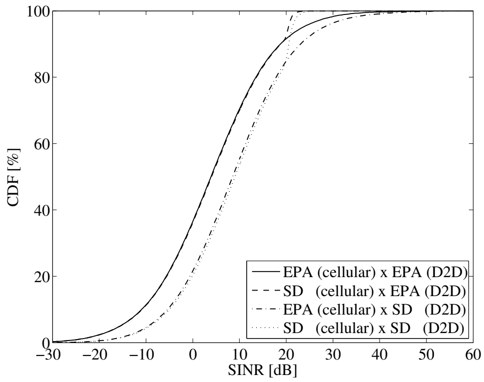
The relative gains in terms of total system spectral efficiency and power saving achieved by applying the SD algorithm to cellular and D2D communications in comparison to the EPA scheme are summarized in Table 4.1 for the two considered operation points. The application of SD in D2D communications always provides a better relative performance for both operation points. As expected, while the operation point P_1 provides better relative gains for the total system spectral efficiency, P_2 performs better in power saving.

In order to protect the cellular communications, the SD algorithm applied to cellular

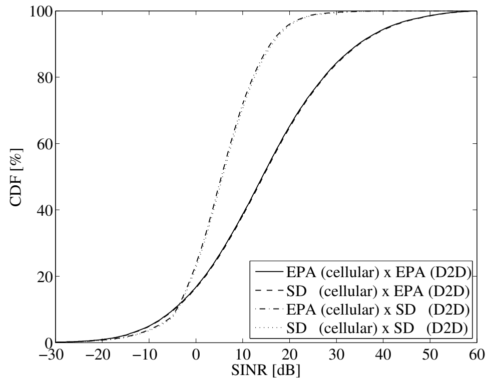
Table 4.1: Relative gains of performance by applying the SD algorithm to cellular and D2D communications.

	Total spectral eff. gain		Power saving	
	P_1	P_2	P_1	P_2
SD in cellular transmitters	$+1\,\%$	$-19\,\%$	$5\,\%$	$57\,\%$
SD in D2D transmitters	$+7\,\%$	$-\ 5\,\%$	$49\,\%$	$84\,\%$

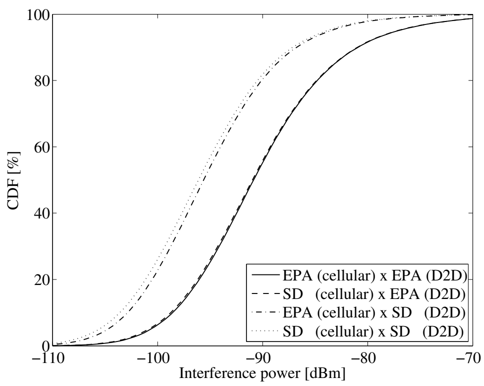
transmitters is set to use the operation point P_1 and the SD algorithm applied to D2D transmitters is set to use P_2. Figure 4.2 presents the Cumulative Distribution Function (CDF) of SINR and interference power perceived by cellular and D2D receivers.



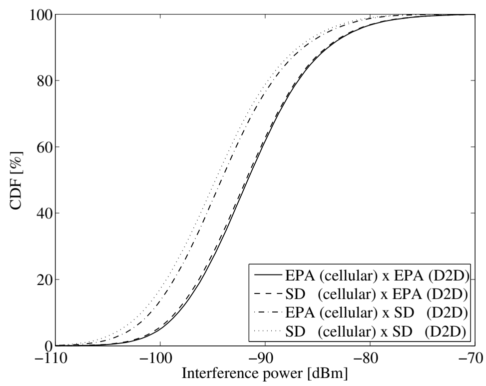
(a) SINR of cellular communications.



(b) SINR of D2D communications.



(c) Interference power of cellular communications.



(d) Interference power of D2D communications.

Figure 4.2: SINR and interference power of cellular and D2D communications by applying SD and EPA schemes.

Observing Figure 4.2(a), when the SD algorithm is applied to cellular communications the SINR and interference curves are practically maintained in comparison to those obtained using EPA. Following results shown in Table 4.1, the operation point P_1 has the best performance in terms of total system spectral efficiency. For this point, the highest SINR levels achieved by cellular communications are marginally reduced while D2D communications maintain the same SINR levels, as shown in Figure 4.2(b). In addition, the power reduction of cellular transmitters does not contribute to the reduction of the interference power perceived by both cellular and D2D receivers, as shown in Figures 4.2(c) and 4.2(d). In general, interfering cellular transmitters are far away from D2D receivers (which only happen to be inside hotspot zones at cell-edges) and from cellular receivers located in other cells.

When the SD algorithm is applied to D2D communications the high SINR levels achieved by D2D communications are reduced, as shown in Figure 4.2(b), and the SINR levels of cellular communications are considerably improved, as presented in Figure 4.2(a). This occurs because, in general, D2D transmitters act as interfering sources quite close to cellular receivers while cellular transmitters are quite distant from D2D receivers since these are inside hotspot zones at cell-edges. Besides that, D2D receivers are more distant from their interfering D2D transmitters, which are regularly distributed over the multi-cell coverage area at cell-edges, than cellular receivers.

When the SD algorithm is applied to both cellular and D2D communications at once, it is possible to notice only tiny gains on the reduction of interference power levels, as shown in Figures 4.2(c) and 4.2(d).

Figure 4.3 presents the system spectral efficiency for cellular communications, D2D communications and both communications modes considering the SD algorithm applied to D2D communications in both operation points P_1 and P_2.

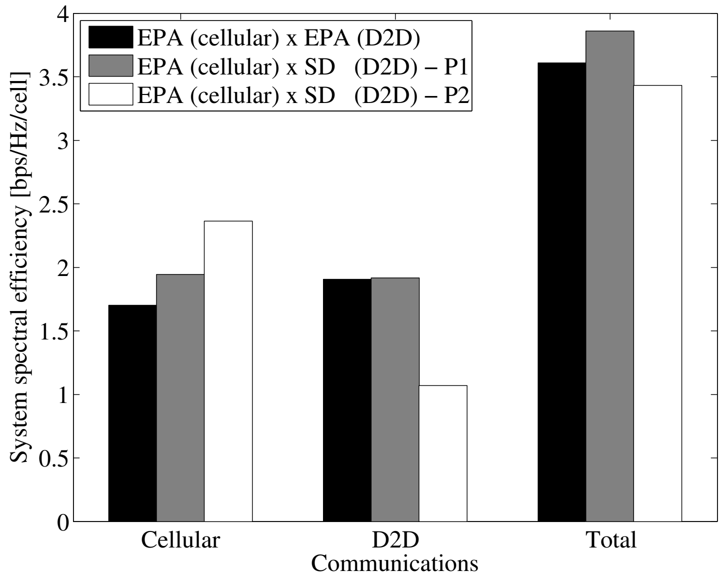


Figure 4.3: System spectral efficiency by applying SD and/or EPA to cellular algorithms and/or D2D transmitters.

As observed in Figure 4.3, the cellular communications always have their performance improved when the SD algorithm is applied to D2D communications for both operation points P_1 and P_2. For the operation point P_1, there is a reduction of $49\,\%$ on the power of D2D transmitters, as shown in Table 4.1, while the performance of D2D communications is practically maintained. The system spectral efficiency relative gains by applying the SD algorithm to D2D communications in comparison to the EPA scheme are summarized in Table 4.2.

Table 4.2: Relative gains of system spectral efficiency by applying the SD algorithm to D2D communications.

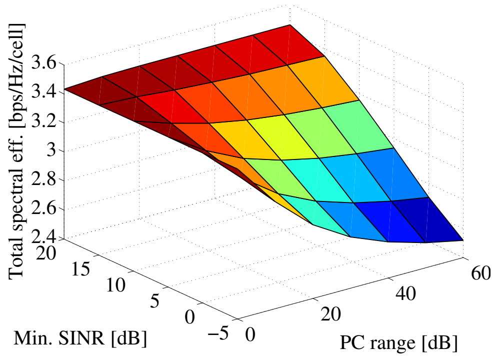
	Cellular gain	D2D gain	Total gain
P_1	$+14\,\%$	$0\,\%$	$+7\,\%$
P_2	$+39\,\%$	$-44\,\%$	$-5\,\%$

As shown in Table 4.2, there is a considerable improvement on the system spectral efficiency of cellular communications for both operation points, which is accompanied with high reduction on the transmit power of D2D transmitters ($49\,\%$ for P_1, as mentioned before, and $84\,\%$ for P_2) as shown in Table 4.1. The main reason for the gains is due to the SDPC has a range of target SINR, while EPA provides a fixed transmit power.

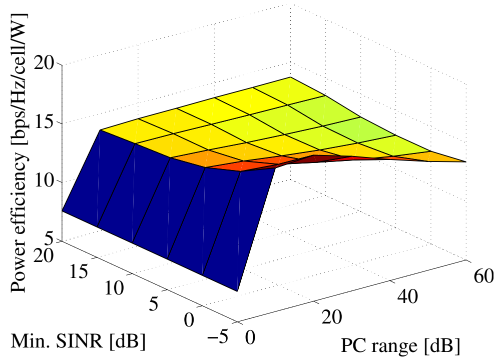
4.1.2 Power Control Evaluation in a Micro-cell Scenario (Uplink)

Section 4.1.1 showed results regarding the DL. The focus of this section is the UL in a Micro-cell scenario, which is aligned with the LTE architecture [60, 63, 64, 66]. The main parameters considered in the simulations are summarized in Table 2.3, a load of 4 users are considered.

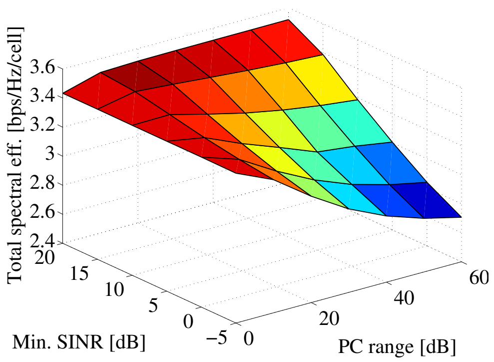
4.1.2.1 LTE PC schemes and SDPC



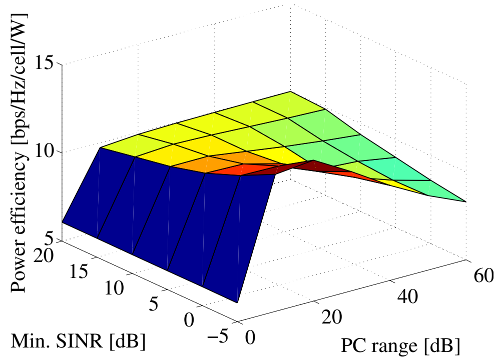
(a) Total spectral efficiency (SDPC in cellular and No-PC in D2D links).



(b) Cellular Power efficiency (SDPC in cellular and No-PC in D2D links).



(c) Total spectral efficiency (No-PC in cellular and SDPC in D2D links).



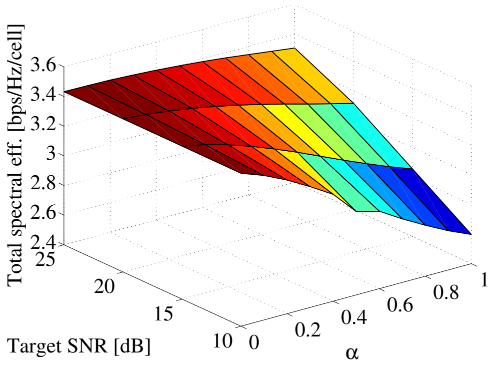
(d) D2D Power efficiency (No-PC in cellular and SDPC in D2D links).

Figure 4.4: Calibration of the SDPC scheme by applying it to cellular or D2D links. The PC range $\Delta_P = 0\,\mathrm{dB}$ gives the performance of fixed power approach. Minimum target SINR values are simulated until $\Gamma_{min} = -5\,\mathrm{dB}$ because the SINR threshold of the lowest MCS is $-6.2\,\mathrm{dB}$.

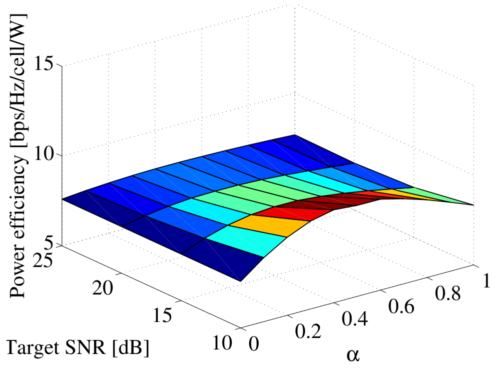
In this section, SDPC, Open Loop Power Control (OLPC), Closed Loop Power Control (CLPC) are step by step analyzed. At first, the SDPC and the OLPC are calibrated and evaluated. After CLPC is calibrated based on the results obtained from OLPC. Finally, all PC schemes are evaluated and compared to EPA and Fixed Power. For performance evaluation, the energy efficiency is measured using the power efficiency metric [2], which gives the ratio of the total system spectral efficiency achieved by cellular and D2D communications to the average transmit power in [bps/Hz/cell/W]. As baseline, the No-PC approach with EPA among scheduled PRBs, i.e., $p_{k,n} = P_{\mathrm{UE}}/N_k$, and the fixed power approach with $p_{k,n} = P_{\mathrm{UE}}/N_{\mathrm{PRB}} = 10\,\mathrm{dBm}, \forall k, n$ are considered.

For calibration purposes, Figures 4.4 and 4.5 show the performance of the SDPC and OLPC, respectively. For each PC scheme, there are operating points responsible for high energy efficiency and reasonable total system spectral efficiency gains.

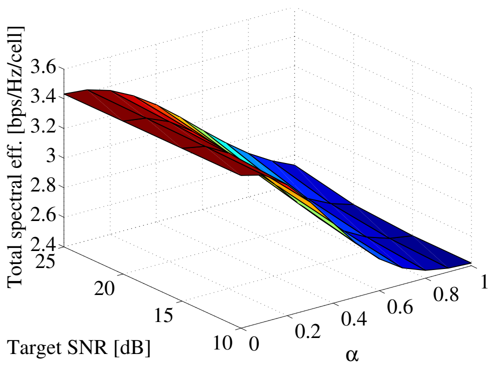
In order to protect cellular communications, operating points are chosen for each PC scheme that maintain the total spectral efficiency or achieve the highest power efficiency gains for D2D communications. The relative performance gains and the considered operating



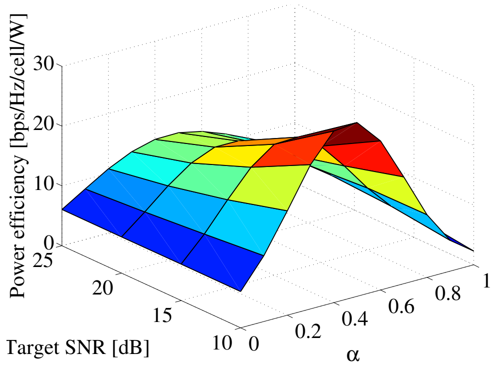
(a) Total spectral efficiency (OLPC in cellular and No-PC in D2D links).



(b) Cellular Power efficiency (OLPC in cellular and No-PC in D2D links).



(c) Total spectral efficiency (No-PC in cellular and OLPC in D2D links).



(d) D2D Power efficiency (No-PC in cellular and OLPC in D2D links).

Figure 4.5: Calibration of the OLPC scheme by applying it to cellular or D2D links. The pathloss compensation factor $\alpha = 0$ gives the No-PC performance.

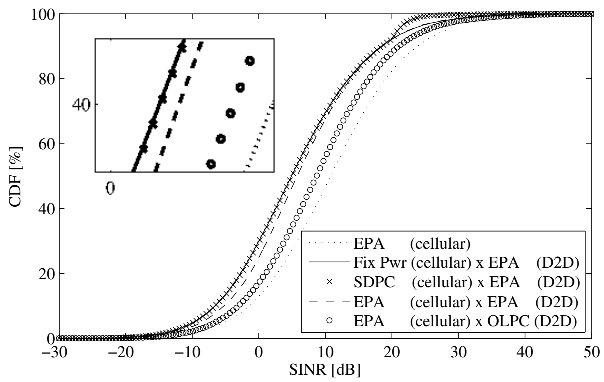
points for each PC scheme are summarized in Table 4.3. While the SDPC scheme performs better for cellular communications, the OLPC scheme is better for D2D communications in terms of power efficiency. Even when OLPC uses, e.g., an operating point ($\Gamma_k = 10\,\text{dB}$, $\alpha = 0.3$) (not shown in the table) providing a total system spectral efficiency loss of $9\,\%$ like the SDPC, its power efficiency gain of $297\,\%$ is even higher than the $114\,\%$ of the SDPC scheme.

Table 4.3: Relative gains by applying SDPC and OLPC to cellular or D2D links in comparison to the No-PC approach (%).

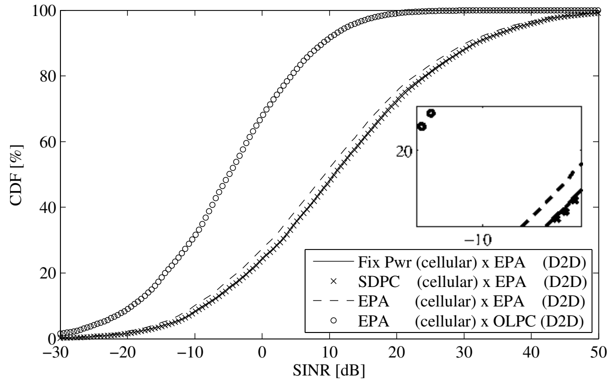
	Total spectral efficiency loss		Power efficiency gain	
	SDPC	OLPC	SDPC	OLPC
Cellular links	0	0	79	3
D2D links	9	20	114	379

Operating points for cellular communications:
SDPC ($\Gamma_{min} = 20\,\text{dB}$, $\Delta_P = 10\,\text{dB}$), OLPC ($\Gamma_k = 25\,\text{dB}$, $\alpha = 0.3$)
Operating points for D2D communications:
SDPC ($\Gamma_{min} = -5\,\text{dB}$, $\Delta_P = 20\,\text{dB}$), OLPC ($\Gamma_k = 10\,\text{dB}$, $\alpha = 0.5$)

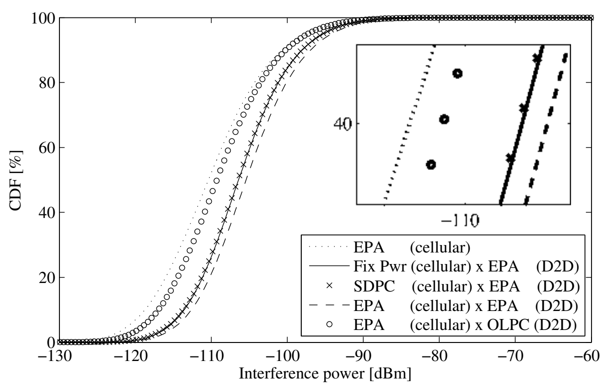
In order to understand the power efficiency gains presented in Table 4.3, Figure 4.6 shows the CDFs of the SINR and interference power levels obtained by applying SDPC and OLPC schemes to cellular or D2D links. By comparing the SDPC scheme to fixed power approach both applied to cellular links, the SDPC scheme only improves the highest SINR levels of cellular links, as shown in Figure 4.6(a). As the SDPC scheme uses the maximum power for all UEs with SINR values below the minimum SINR target, their transmit power values are fixed by Equation (3.11) as in the fixed power approach. The No-PC approach achieves higher SINR levels than the fixed power approach, but its interference power levels are also higher. On its turn, the OLPC scheme reduces the SINR levels of D2D links, because the power reduction does not considerably improve their interference power levels, as shown in Figure 4.6(d), but it provides the closest performance for cellular links compared with the conventional scenario, see Figures 4.6(a) and 4.6(c).



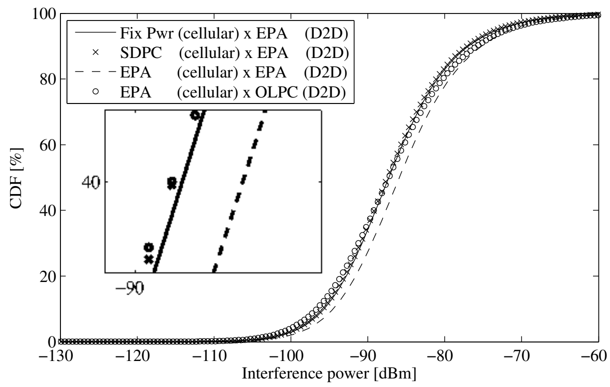
(a) SINR of cellular communications.



(b) SINR of D2D communications.



(c) Interference power of cellular communications.



(d) Interference power of D2D communications.

Figure 4.6: SINR and interference power levels by applying SDPC and OLPC schemes to cellular or D2D links. No-PC and fixed power approaches are considered as baselines. No-PC (cellular) represents the conventional scenario without D2D communications underlaying the cellular network.

As the SDPC scheme aims mainly at the reduction of high SINR levels (which reduces the power consumption without significantly harming the system spectral efficiency) while the OLPC scheme compensates the pathloss even for low SINR levels, the SDPC scheme provides a better power efficiency for cellular communications. For D2D communications, the OLPC scheme achieves a reduced power consumption by exploiting the UEs' physical proximity. As the OLPC scheme applied to D2D links provides the highest energy efficiency gains, Figure 4.7 presents the system spectral efficiency of cellular and D2D communications by applying OLPC to D2D links and no PC for cellular links.

As it can be seen, the factor α can be used to control the performance trade-off between cellular and D2D communications. We also see that for $\alpha = 1.0$, which provides the lowest possible transmit power levels for D2D transmitters ($5\,\mathrm{dBm}$), the system spectral efficiency for D2D communications is practically zero. It means that D2D transmitters are introducing interference to the system but D2D receivers are not achieving the SINR threshold of the lowest MCS to attain communication. Thus, the minimum cost for enabling system spectral efficiency gains for D2D communications considering the most favorable scenario for sharing resources in all cells represents a minimal impact of $11\,\%$ on the system spectral efficiency of cellular UEs. To get gains in the total system spectral efficiency over the conventional

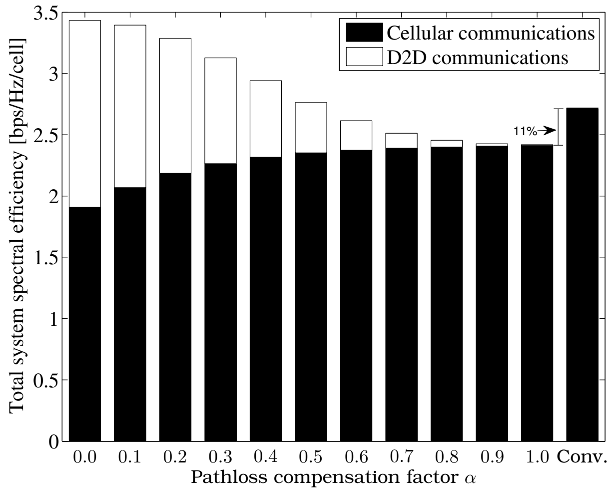


Figure 4.7: Total system spectral efficiency by applying OLPC to D2D links without PC for cellular links (No-PC approach). The pathloss compensation factor α of the OLPC scheme is varied for target SNR $\Gamma_k = 10\,\text{dB}$. The conventional scenario considers the No-PC approach in its cellular links.

scenario, α should be lower than 0.6. For $\alpha = 0.5$, the impact is $13\,\%$, but the power efficiency is maximum, as it can be seen in Figure 4.5(d). The highest impact (which is $30\,\%$) is obtained for $\alpha = 0$, i.e., when the maximum power P_{UE} is employed to D2D links as in the No-PC approach.

The relative performance gains of OLPC for D2D links by varying α are summarized in Table 4.4. Most α values provide huge power saving gains (measured against the total transmit power used for transmission) but low α values are preferred to avoid high system spectral efficiency losses. To achieve high power efficiency gains for D2D links, α should be $\{0.4, 0.5\}$.

Table 4.4: Relative performance gains of OLPC for D2D links compared with no-PC for D2D links (%).

α	0.1	0.2	0.3	0.4	0.5	0.6
Spectral efficiency loss	13	28	43	59	73	84
Power saving gain	52	75	86	91	94	96
Power efficiency gain	81	188	298	373	379	311

Using the same parameters of Table 4.3, it is possible to analyze the CLPC, which is another LTE PC scheme. The parameter $\alpha = 0.5$ is defined as the best value to provide power efficiency at OLPC, see Figure 4.5 and the same α is used at CLPC. The CLPC has a new parameter called dynamic offset compensation factor σ, which needs to be calibrated. It is possible to decrease the SINR level of the best users and increase the SINR of the worst users to different values of σ. Table 4.5 shows the SINR values of the of 5th and 95th percentiles to both communications, and the difference between those percentiles to different values of σ. Remembering if the value of σ is small, the users can achieve the same SINR level. Finally, $\sigma = 0.8$ is set, because it has the smallest difference between percentiles, as shown in Table 4.5.

After the choice of parameters, the PC schemes are evaluated. Figure 4.8 shows the CDFs of the SINR values for cellular or D2D links, as it can be seen in Figure 4.8(a), the behavior of SINR levels of cellular links, when the same PC scheme is applied to both communications. Comparing OLPC and CLPC it is possible to perceive that CLPC improves the worst users without compromising the best users.

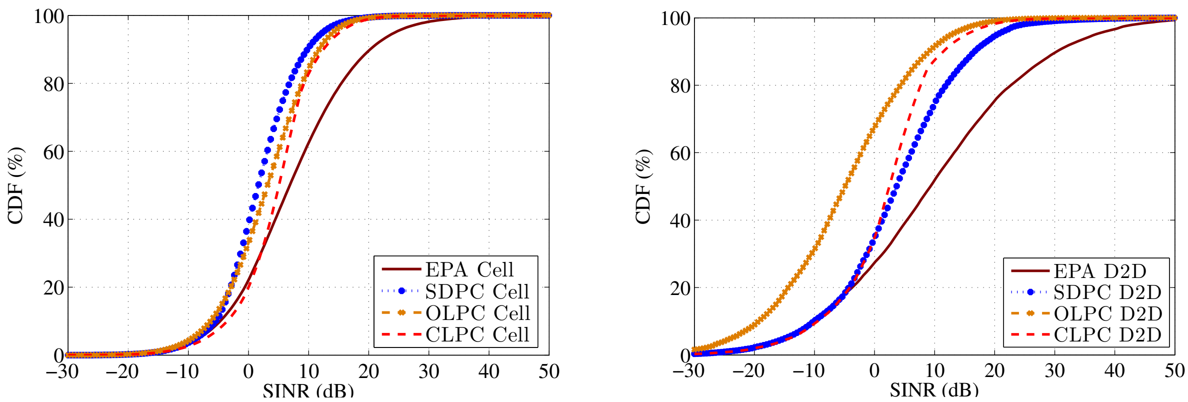
The SDPC modifies the power of users who show SINR between Γ_{max} and Γ_{min} and keeps a fixed power value given by Equation (3.11) to user's SINR values below Γ_{min}. Comparing EPA with both LTE PC schemes and SDPC, a decrease in the SINR level of the users with

Table 4.5: Calibration of σ for CLPC

σ	$\mathrm{SINR}_{5\,\%}$	$\mathrm{SINR}_{95\,\%}$	$\mathrm{SINR}_{95\,\%} - \mathrm{SINR}_{5\,\%}$
Cellular Communication			
0.2	-26.48	-1.34	25.14
0.4	-21.96	0.16	22.12
0.6	-20.45	1.17	21.62
0.8	-15.92	3.18	19.10
1.0	-19.94	9.21	29.10
D2D Communication			
0.2	-13.41	8.70	22.11
0.4	-10.39	8.21	18.60
0.6	-9.38	8.21	17.59
0.8	-7.87	9.20	17.07
1.0	-10.00	10.73	20.73

high SINR level can be seen, and this behavior provides a better power efficiency to cellular communication.

Figure 4.8(b) presents SINR levels of D2D links, when PC scheme is applied to both communications. It can be noted that the SINR has the worst level when OLPC is applied in D2D links. Special attention must be given to the OLPC and CLPC, since there is a fall of SINR level when OLPC is used. This fall is due to the high path gain caused by proximity between D2D transmitter and receiver; however, CLPC is not affected, because there is a feedback that adjusts transmit power levels. The SDPC keeps the same SINR to users with low SINR level and improves the users with high SINR level in relation the CLPC.



(a) SINR of cellular communications.

(b) SINR of D2D communications.

Figure 4.8: SINR by applying power control schemes to cellular and D2D links.

To further analyze the performance of PC schemes, Figure 4.9 shows the behavior of PC schemes in relation to spectral and power efficiency. PC schemes with high spectral efficiency are situated at the top of figure and high power efficiency are situated in the right of the figure. From a cellular communications point of view, it is possible to note that EPA has the highest spectral efficiency and the lowest power efficiency among the studied PC schemes, because it always uses high transmit power. CLPC and OLPC have about the same power efficiency, however, CLPC has a feedback, which increases its spectral efficiency. Both LTE PC schemes have a spectral efficiency higher than SDPC, because SDPC provides a balance between spectral and power efficiency. So that the SDPC keeps a reasonable spectral efficiency and provides a gain of $70\,\%$ in power efficiency compared with LTE PC schemes.

Considering D2D communications, EPA keeps the same behavior of the cellular communications. Both LTE PC schemes have low level of spectral efficiency, however, OLPC has a little more decreased spectral efficiency, achieving the highest power efficiency. When SDPC and LTE PC schemes are compared, it is possible to note that SDPC shows better spectral efficiency. However, when power efficiency is compared, SDPC has a gain of 35 % in relation to CLPC and a loss of 120 % in relation to OLPC. Another result that can be noted is that PC schemes in the middle of the Figure 4.9, it can be combined to provide a tradeoff between spectral efficiency and power efficiency.

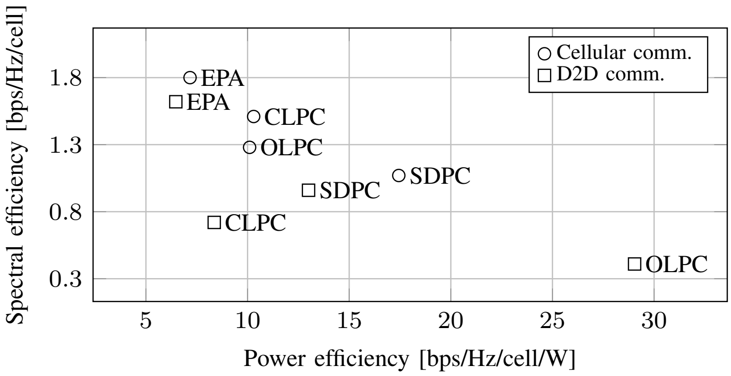


Figure 4.9: Performance of PC schemes for cellular and D2D communications.

4.1.2.2 Closed Loop Soft Dropping (CLSD) a hybrid PC scheme

The CLSD is a hybrid PC scheme based on CLPC and SDPC. For performance evaluation, CLSD parameters are set with the values that have provided a good performance to CLPC and SDPC in their original form in the Section 4.1.2.1. The parameters are summarized in Table 4.6.

Table 4.6: CLSD parameters

Parameter	Cellular	D2D
α	0.3	0.5
β	0.8	0.8
Δ_P	10 dB	20 dB
Γ_{max}	25 dB	25 dB
Γ_{min}	20 dB	−5 dB

β and σ have the same function

Figure 4.10 shows the results obtained in terms of spectral efficiency. CLSD provides the best results of total spectral efficiency, due to knowledge of path gain, current SINR and to be able of modifing target SINR.

Another way to view results of Figure 4.10 is in terms of relative gains. Table 4.7 summarizes spectral efficiency relative gains when CLSD is compared with other algorithms. CLSD provides a reasonable performance to cellular communication with the highest and lowest relative gain are of 91 % and 22 % compared with SDPC and EPA, respectively. From a D2D communication point of view, CLSD has a reasonable spectral efficiency gains with the highest and lowest relative gains are 275 % and −7 % compared with OLPC and EPA, respectively.

Figure 4.11 determines the power efficiency of the PC schemes. CLSD achieves 18 bps/Hz/cell/W for cellular communications, which is the best result among all studied PC schemes, while EPA has the lowest power efficiency achieving 7 bps/Hz/cell/W. In other words, CLSD manages smartly the power transmit and EPA wastes it, because the transmit power is high for all users when EPA is used. From D2D point of view, CLSD provides the second best

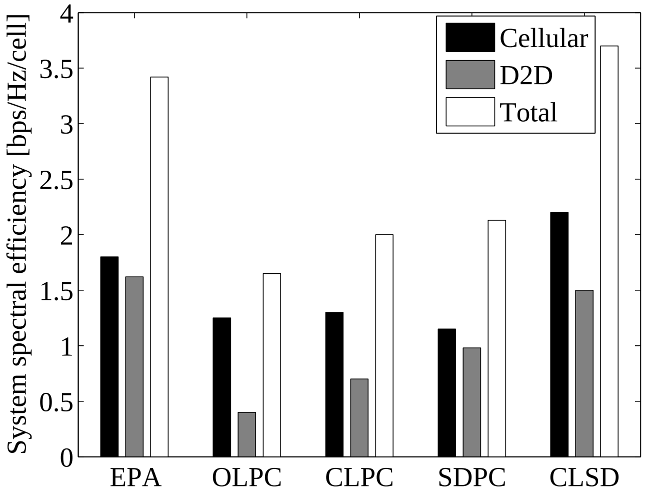


Figure 4.10: Spectral efficiency of PC schemes for cellular and D2D communications.

Table 4.7: Spectral efficiency relative gains applying CLSD compared with other PC schemes (%).

	EPA	OLPC	CLPC	SDPC
Cellular links	22	76	69	91
D2D links	-7	275	114	53
Total	8	124	85	73

D2D power efficiency. The reason of this high power efficiency for OLPC is the path gain of D2D communications described in Section 4.1.2.1.

The power efficiency relative gains of CLSD compared with other PC schemes are described in Table 4.8. It is important to highlight the highest relative gain to cellular and D2D communications, which are 157 % and 100 % when compared with EPA.

It is important to highlight that the CLSD has this good performance due to knowledge of path gain, current SINR and to be able of modify target SINR. These information are useful to improve spectral and power efficiency of the system, however, the complexity of CLSD and the number of subcarriers used to feedback is higher compared with other PC schemes.

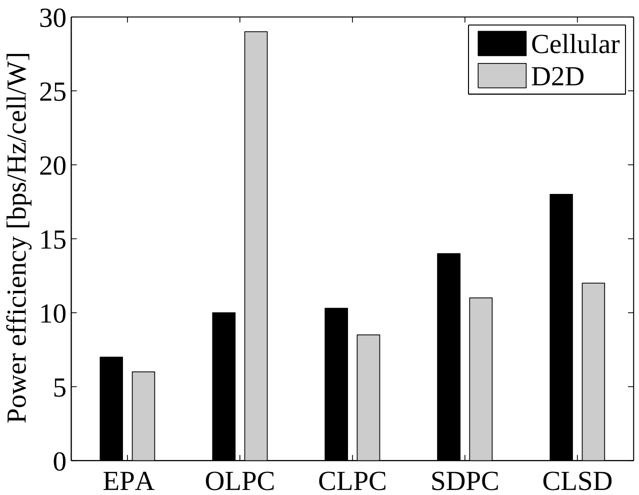


Figure 4.11: Power efficiency of PC schemes for cellular and D2D communications.

Table 4.8: Power efficiency relative gains applying CLSD compared with other PC schemes (%).

	EPA	OLPC	CLPC	SDPC
Cellular links	157	80	75	29
D2D links	100	-59	41	9

4.1.2.3 Impact of loads in PC schemes

The analysis of PC schemes in a scenario with different loads is important to understand if they explore well the diversity that each user provides in the system. In the simulations, both communications use the same PC scheme and its total spectral and power efficiency are evaluated. It is seen in Figure 4.12 that EPA achieves good spectral efficiency when the offered load increases, it surpass SDPC, OLPC and CLPC, however, this efficiency range decreases for high loads, because EPA does not explore well the diversity that each user provides.

When SDPC is used in both communications, it achieves better results than OLPC and CLPC, because it has feedback and variable target SINR. These two features offer the opportunity of increasing the SINR of the worst users and keep reasonable SINR levels for the best users.

Taking a look at LTE PC schemes, it is perceptible that the OLPC and CLPC have a similar behavior. However, OLPC has a marginal loss due to the lack of feedback, which is present in CLPC. Finally, the CLSD has achieved the best performance for all considered loads, because it uses the benefits of both CLPC and SDPC.

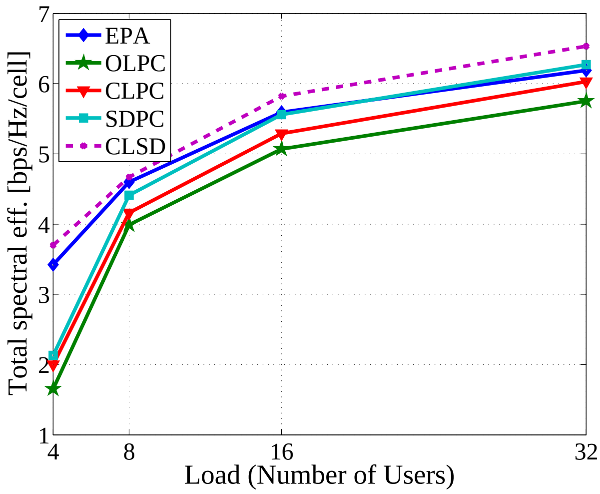


Figure 4.12: Total spectral efficiency comparison for different loads.

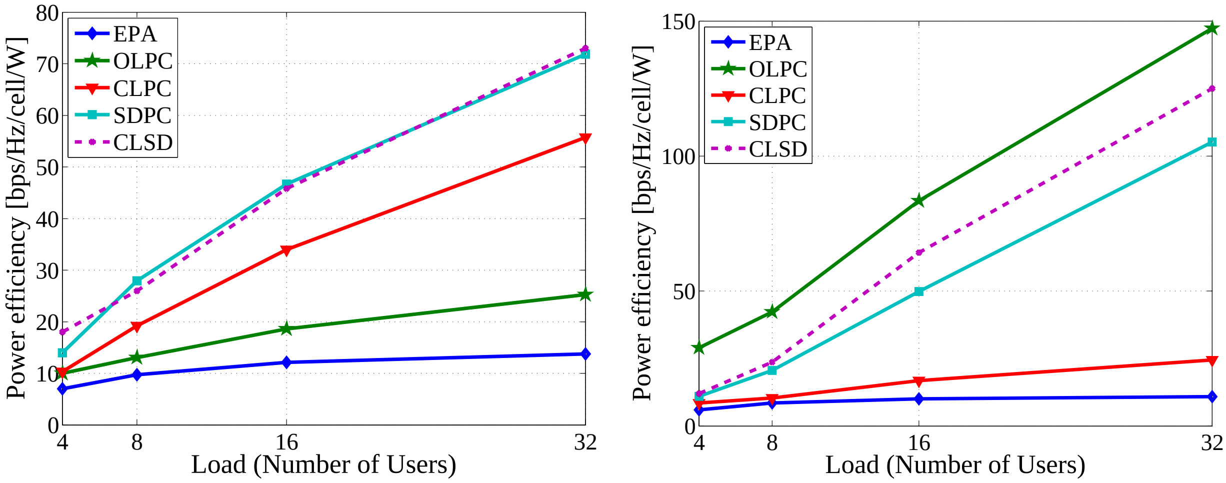
From Figure 4.13(a), one sees that EPA shows the worst result in terms of power efficiency to cellular communications. This is an indication that EPA fails in explore the diversity of users, given that it always uses the maximum transmit power regardless of user SINR.

The OLPC and CLPC provide a similar power efficiency for four users in each cell. However, CLPC for high loads attains a significant power efficiency gain compared with OLPC. This results show that only knowledge of path gain is not enough to provide a good power efficiency to cellular communications, because it shows a low information about user in the network to PC scheme. In order to offer better power efficiency to cellular communications SDPC and CLSD are the best choices, which achieve good performance in a scenario with high loads due to explore well the diversity.

It may be seen in Figure 4.13(b) that incorporating EPA, D2D communications do not show good performance in terms of power efficiency. It is possible to note that the power efficiency decreases after 8 users in a cell, because the interference level is so high that harms the spectral efficiency of D2D users. The OLPC keeps a good performance for all offered loads. This behavior can be explained by the high value of the path gain due to the proximity of communications occurring inside the hotspot.

It is interesting to see that CLPC shows a low power efficiency compared with OLPC, because it tries to keep a good spectral efficiency, therefore, it does not decrease the transmit power as much as OLPC. The SDPC and CLSD for low loads have a similar power efficiency for D2D communications, however, CLSD is more efficiency for high loads.

The reason for the power efficiency gain of CLSD is that it has not only information about the path gain, which decreases the power transmit like OLPC, but also it has variable target SINR that provides a good total spectral efficiency.



(a) Power efficiency for cellular communications. **(b)** Power efficiency for D2D communications.

Figure 4.13: Power efficiency comparison for different loads in cellular and D2D communications.

4.1.2.4 Imperfect CSI

Features such as multi-user scheduling operating in fading channels can be used to explore diversity gains and improve the quality of communications in cellular networks. For this purpose, precise CSI (i.e. perfect CSI) needs to be available at the eNB to perform rate adaptation and scheduling. However, in real cellular networks, CSI is impaired by channel estimation errors and feedback delays. This impact is high in networks where the data is sent to a central point, because high backhaul latency can cause CSI imperfections, resulting in performance degradations [75, 76].

In order to understand the effects of imperfect CSI in D2D communications underlaying cellular networks, a scenario where both communications use the same PC scheme with the parameters described in Section 4.1.2.1 and Section 4.1.2.2 is used. Therein, each site has 16 UEs operating in UL. The reason for choosing this scenario is due to the interference level and effects of delay feedback being significant.

Figure 4.14 shows the total spectral efficiency to different delays ranging from 0 TTI (no delay) to 5 TTIs. It is noticeable that without feedback delays the CLSD has the best spectral efficiency, followed by EPA, SDPC, CLPC and OLPC. All PC schemes decrease its spectral efficiency when delay increases, however, each PC scheme has a different drop rate. The EPA and OLPC have slight loss of spectral efficiency compared with other PC schemes, because EPA and OLPC are not influenced significantly by feedback. In other words, EPA does not need feedback, because it always uses the same transmit power and OLPC requires only G (path gain), which does not suffer a significant modification from one Transmission Time

Interval (TTI) to another. The main factor that harms EPA and OLPC is scheduling, because eNB allocates PRB to users, which decrease their quality of channel from one TTI to another.

The CLPC has an accentuated loss of spectral efficiency compared with EPA and OLPC, because CLPC computes transmit power based on G (path gain) and current SINR, so CLPC computes transmit power using two out-of-date measures.

The SDPC and CLSD have the worst spectral efficiency for high delays, because SDPC is dependent on the current SINR, target SINR and previous transmit power. Moreover, CLSD is not only dependent on same parameters as SDPC measures, but also on CLPC measures.

The PC schemes have a similar spectral efficiency when the delay increases up to one TTI, the spectral efficiency keeps between $4.8\,\mathrm{bps/Hz/cell}$ and $5.4\,\mathrm{bps/Hz/cell}$. This difference becomes expressive when delay is higher than one TTI, in this case the difference between values achieves $3.4\,\mathrm{bps/Hz/cell}$ when delay is 5 TTIs.

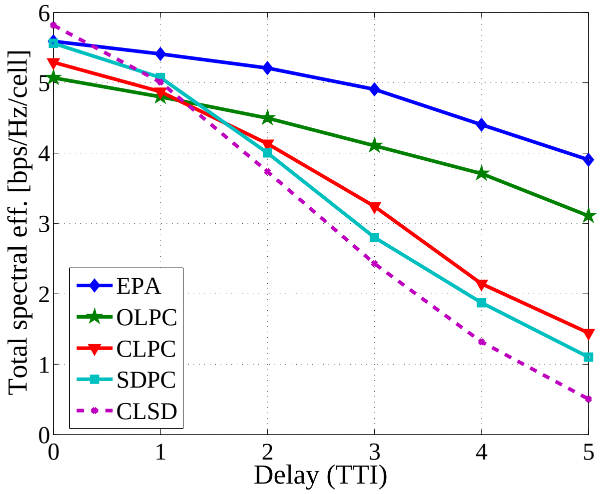


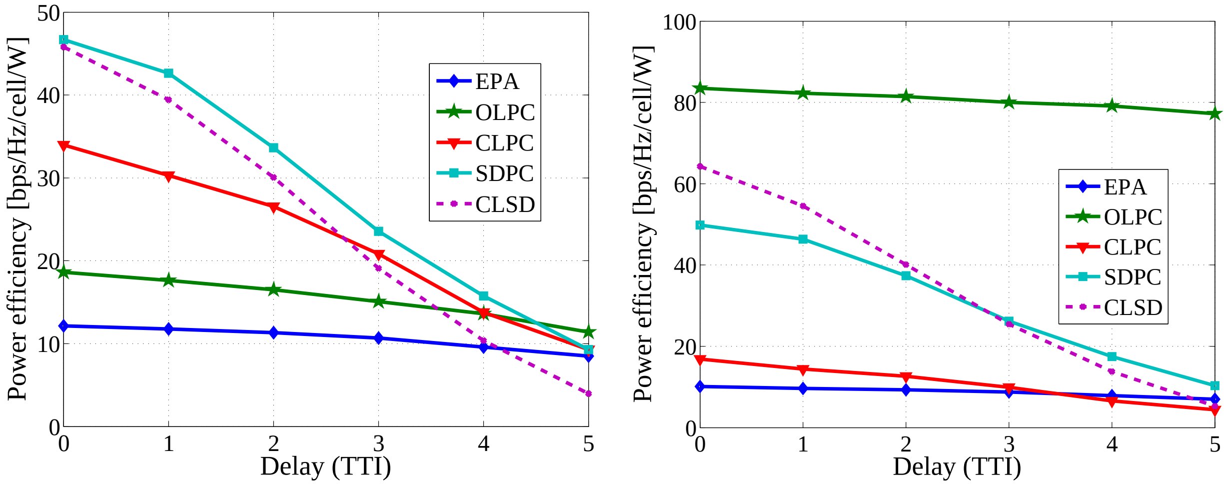
Figure 4.14: Total spectral efficiency for different delays.

As it is shown in Figure 4.15(a), cellular power efficiency has the same behavior of spectral efficiency, that is to say, power efficiency decreases for high delay. SDPC and CLSD have the best results in terms of power efficiency when CSI is perfect, however, these PC schemes are affected negatively after a delay of 2 TTIs. CLPC has an acceptable power efficiency for low delay values, however, it is outweighed by OLPC for high delay. EPA has the worst results in terms of power efficiency up to a delay of 4 TTI and after this delay value, CLSD has the worst performance due to the number of out-of-date measurements.

Figure 4.15(b) presents D2D power efficiency, it is noticeable that OLPC has the lowest loss of power efficiency compared with other PC schemes. This behavior is due to G (path gain) of D2D communications to be similar from one TTI to another, due to the proximity among UEs communicating in D2D mode. Among the PC schemes, SDPC and CLSD have a high power efficiency loss, while CLPC keeps a reasonable performance.

The PC schemes based on many measures suffer a significant loss of spectral and power efficiency, when feedback delay occurs. In terms of total spectral efficiency and cellular power efficiency, feedback delay becomes significant when the system has a delay higher than 2 TTIs, thus it is better to use PC schemes simpler to provide the best efficiency to the system.

It is interesting to note that OLPC keeps a good power efficiency to D2D communications independent of the delay, because OLPC provides transmit power based on the metric G (path gain), which does not vary significantly among TTIs.



(a) Power efficiency for cellular communications. **(b)** Power efficiency for D2D communications.

Figure 4.15: Power efficiency for different delays in cellular and D2D communications.

4.1.2.5 Convergence of SD

It is important to verify the convergence of SD, an analytical analysis of convergence is demonstrated in Appendix A. In this master's thesis, a complementary analysis using computational simulations is also realized. It is important to make clear that the convergence is influenced by parameters values, loads, cell size and CSI. So, a scenario with 8 users, using SD parameters $\Delta_P = 30\,\text{dB}$, $\Gamma_{max} = 25\,\text{dB}$ and $\Gamma_{min} = -5\,\text{dB}$ was selected for analysis considering both cellular and D2D communications.

In order to show the convergence of SD, it was used Mean Squared Error (MSE), which is based on values of target SINR $\Gamma_{k,n}$ and current SINR $\gamma_{k,n}$ of user k scheduled to PRB n in each cell site. In Figure 4.16, I illustrate the step-by-step on how the convergence is calculated. First step is to create a matrix that contains the difference between target SINR $\Gamma_{k,n}$ and user SINR $\gamma_{k,n}$ squared. Second step is to create another matrix, where each element corresponds the mean of difference between target SINR $\Gamma_{k,n}$ and user SINR $\gamma_{k,n}$ squared to each TTI. Third step represents the mean to each sample. Finally, the last step aims at the normalization of the elements.

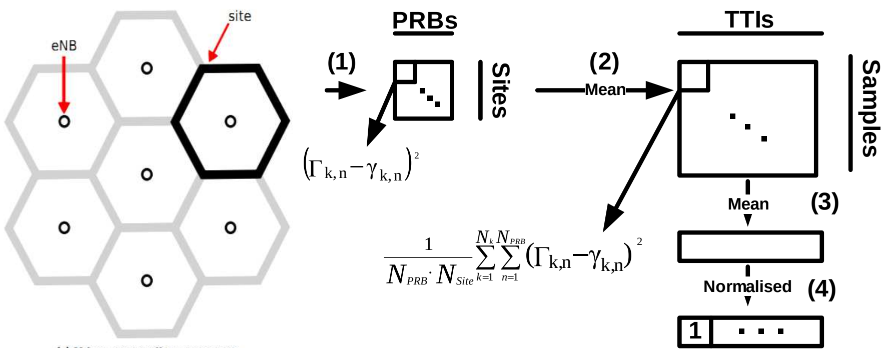


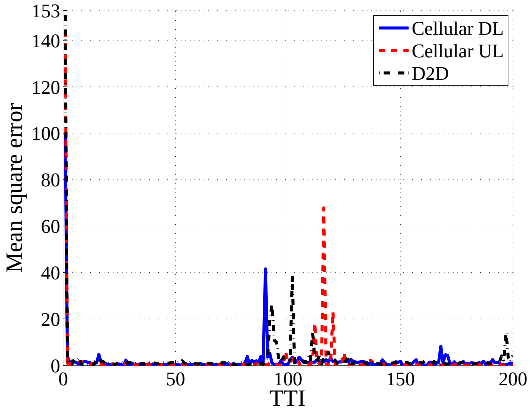
Figure 4.16: Detailed description of calculation of convergence.

Figure 4.17(a) shows the MSE for the SINR of cellular and D2D communications, the mean of difference between target SINR $\Gamma_{k,n}$ and user SINR $\gamma_{k,n}$ squared. It shows that SD keep a decrease from 153 to 5, this means that the variation of the difference was about $10\,\text{dB}$, in other words, the SDPC improved the accuracy of target SINR in $10\,\text{dB}$.

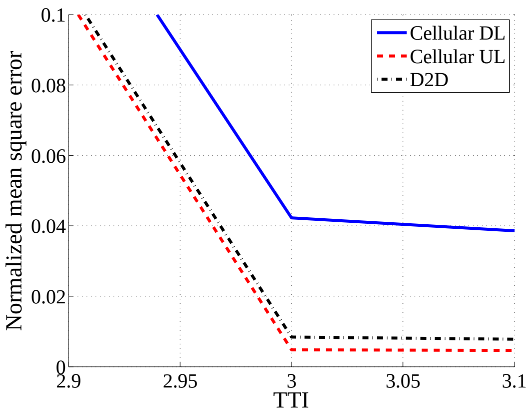
Figure 4.17(b) shows the convergence using normalization of cellular communications in DL/UL and D2D communications, respectively. In both communications, the Normalized

Mean Square Error (NMSE) achieves values lower than $0,1$ in 3 TTIs (3 ms).

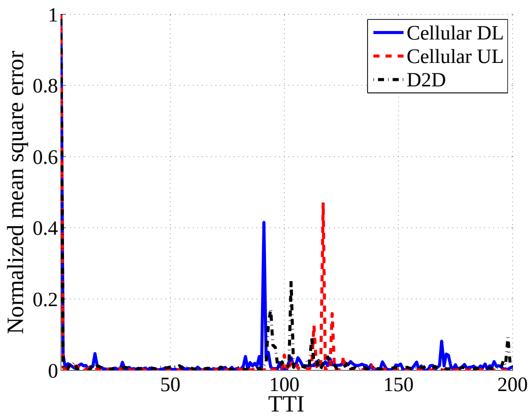
Figure 4.17(c) shows the behavior of convergence to 200 TTIs (200 ms). It is interesting to note that some peaks appear in the figure. These peaks are due to MaxGain scheduling, which modifies the PRB allocation during the simulations, thus changing channel parameters. Even though, SD is able to return the normal operation after 3 or 4 TTIs (3 ms or 4 ms).



(a) Convergence during 200 TTIs using MSE.



(b) Convergence to first values of TTIs using NMSE.



(c) Convergence during 200 TTIs using NMSE.

Figure 4.17: Convergence of SD.

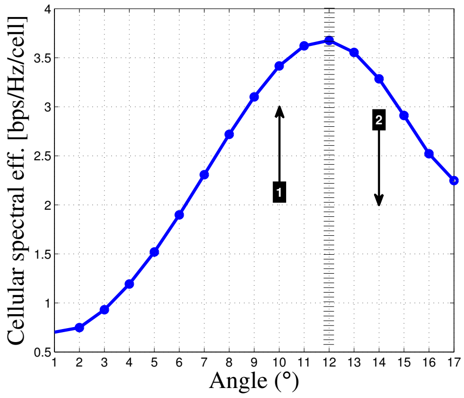
4.2 Antenna Downtilt

This section investigates the impact of electrical downtilt in an urban-macrocell scenario where D2D communications underlay a cellular network. The downtilt evaluation is realized in the DL through system-level simulations, which are aligned with the LTE architecture [60, 63, 64, 66].

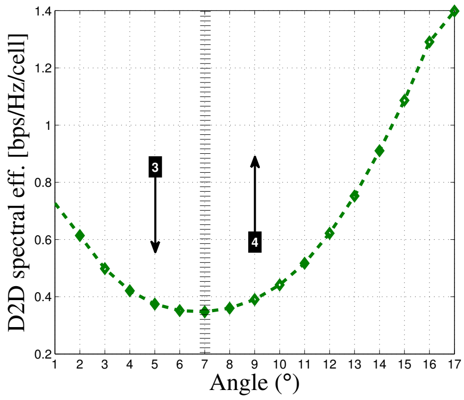
4.2.1 Impact of Downtilt in a cellular network with D2D

For the performance evaluation, the scenario detailed in Table 2.3 is used. Initially, only EPA is utilized to determine the power of the UEs. This strategy is useful to better understand the behavior of downtilt in a scenario with D2D communications, because in this scenario the gains are not influenced by PC scheme.

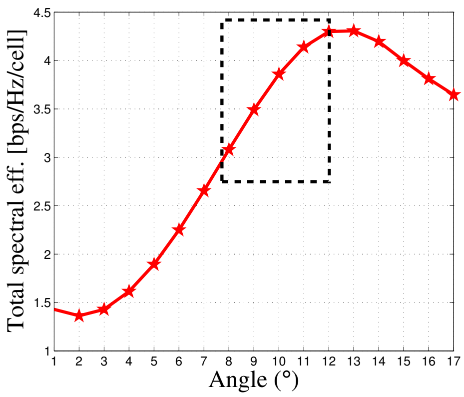
In Figure 4.18 shows the power and spectral efficiency values as functions of the downtilt angle. It is possible to note that cellular spectral efficiency has good values when the downtilt angle increases up to $12°$ (arrow number 1) since cell isolation is improved and interference is reduced when the downtilt angle increases (Figure 4.18(a)). However, after this angle the cellular users performance begins to decay, since too large downtilt angles reduced coverage (arrow number 2).



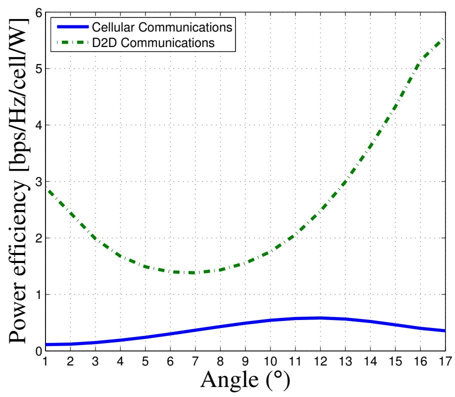
(a) Cellular spectral efficiency.



(b) D2D spectral efficiency.



(c) Total spectral efficiency.



(d) Power efficiency.

Figure 4.18: Behavior of spectral and power efficiency for different levels of tilt.

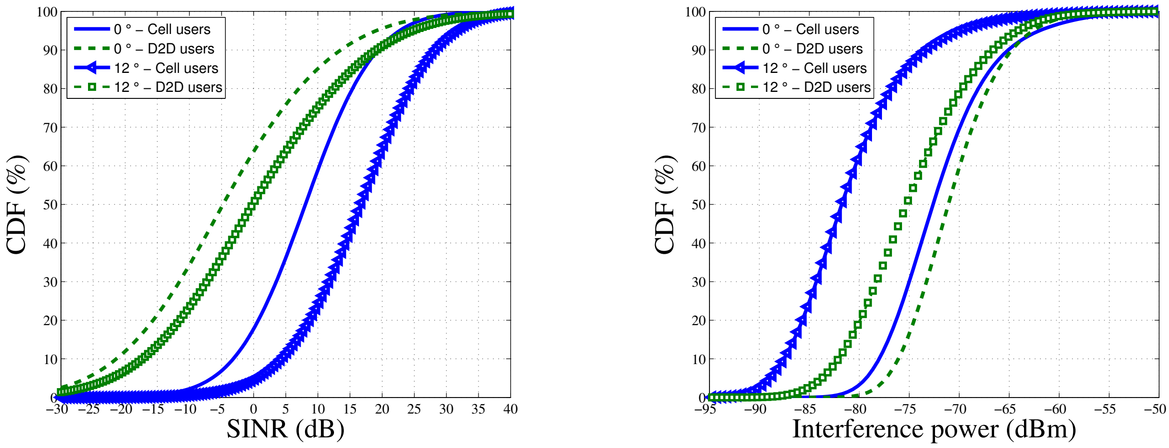
From a D2D point of view (Figure 4.18(b)), spectral efficiency has the opposite behavior compared with cellular UEs. At first, a spectral efficiency decline occurs, which reaches the worst result at 7° (arrow number 3), since the Evolved Node B (eNB) interference is focused in the hotspot area near the cell edge. After 7°, it is possible to improve D2D spectral efficiency, because the interference inside hotspot zone decreases (arrow number 4).

Figure 4.18(c) shows the total spectral efficiency to downtilt angles between 1° and 17°. The rectangle determines the range of downtilt angles where the total spectral efficiency is higher than without downtilt (0°) and does not harm the coverage area of cellular users. In other words, angles between 8° and 12° improve spectral efficiency of system, while preserving cellular communications.

In the following, it is adopted an angle of 12° for downtilt in the simulations, since it corresponds to the angle that provided the best total spectral efficiency in the previous evaluation. Then, the influence of the downtilt angle in the SINR and interference curves is analyzed, as illustrated in Figure 4.19. It is shown in Figures 4.19(a) that using downtilt it is possible to improve the SINR curves for cellular and D2D communications. The analysis at 50 % in Figure 4.19(b) confirms the results of the SINR curves, because the interference of cellular and D2D communications decreases 10 dB and 4 dB, respectively.

Figure 4.20 compares the system spectral efficiency of cellular and D2D communications applying 12° as downtilt angle at eNB.

D2D communications do not get a significant gain in spectral efficiency, while cellular communications get a performance which is better than in the conventional scenario, where 0° of downtilt is used. The total spectral efficiency achieves 58 % of gain, so that it can be concluded that angles between 8° and 12° offer the possibility to keep D2D communications'



(a) SINR Curves.
(b) Interference Curves.

Figure 4.19: SINR and interference levels by applying downtilt.

quality while improving considerably the performance of cellular communications. In terms of power efficiency, the behavior is shown in Figure 4.18(d) and the values are summarized in Table 4.9. It is possible to note that angles between 11° and 12° have better power efficiency to both communications, while angles lower than 11° do not have good power efficiency for D2D communications.

Table 4.9: Power efficiency relative gains for different downtilt angles compared without downtilt (%).

	8°	9°	10°	11°	12°
Cellular communications	4%	22%	40%	53%	65%
D2D communications	-29%	-23%	-0.1%	1.7%	22%

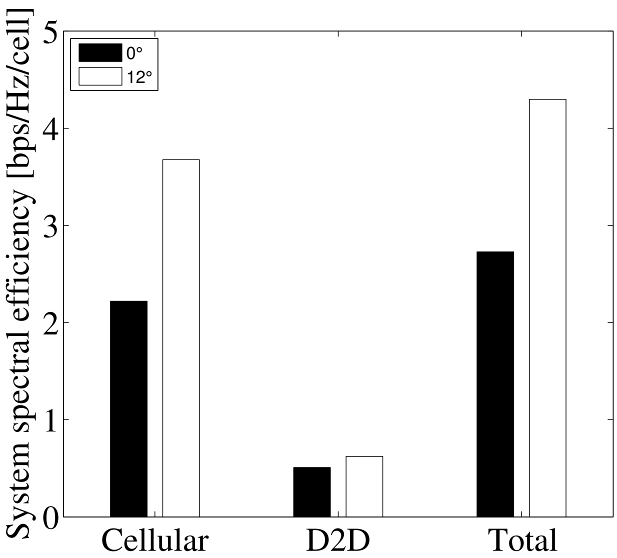


Figure 4.20: System spectral efficiency of cellular and D2D communications in scenario with and without downtilt.

In Figure 4.21, the impact of outage to both communications and the outage reduction compared without downtilt can be seen. This outage reduction represents the number of users who previously were in outage and currently are not in outage. For example, 10 users are in outage without downtilt and an outage reduction of 50 % with downtilt means that 5 of the 10 users are not in outage currently.

The positive impact of downtilt occurs in a range of angles between 7° and 15° which are named critical angles because angles lower than 7° and higher than 15° do not reduce the outage to cellular communications. Angles out of this range must be avoided.

Analyzing the cellular communications, it is possible to note that for angles from 7° to 12° a reduction of the outage level occurs due to decrease of the intercellular interference level. After 12°, the coverage radius of the eNB reduces to each angle, leaving cellular users without communication.

From the D2D communication point of view, the outage reduction decreases for low downtilt angles. However, it keeps a gain in relation to case without downtilt. After 7° a decrease of the outage level occurs because the interference level inside the hotspot decreases.

It is important to clarify that the focus is to provide the best outage level to cellular users. When 12° of downtilt is used, it is possible to achieve an outage reduction of 75 % for cellular communications, while D2D communications achieve a gain of 28 %.

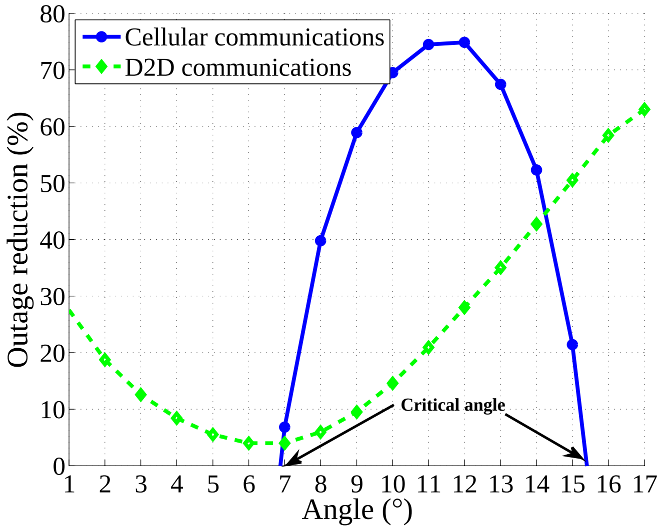


Figure 4.21: Outage reduction for different levels of tilt.

4.2.2 SDPC in a Downtilt scenario

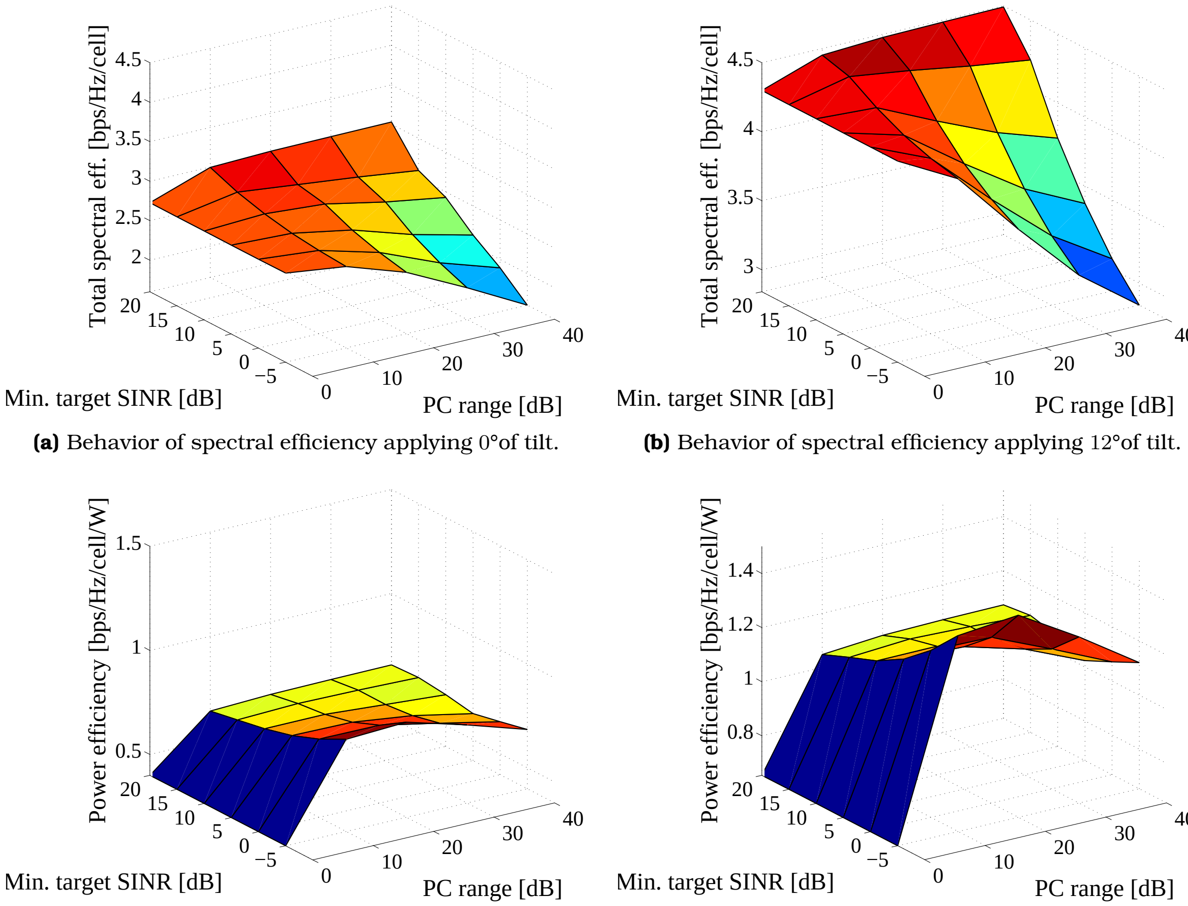
Section 4.2.1 shows the impact of downtilt in a scenario only with EPA. In this section, the performance of SDPC is studied jointly with downtilt. The SDPC is evaluated using 12°of downtilt, because this angle achieved good results in terms of spectral and power efficiency with EPA.

Figure 4.22 shows the total spectral efficiency and power efficiency, when cellular and D2D communications use SDPC and EPA, respectively. Figure 4.22(a) shows the case where SDPC does not use downtilt. When a downtilt of 12° is used (see Figure 4.22(b)) the spectral efficiency increases for all sets of parameters analyzed. The highest possible spectral efficiency ($\Delta_P = 40$ dB and $\Gamma_{min} = 20$ dB) using SDPC without downtilt is 3 bps/Hz/cell, however, it is possible to achieve 4.5 bps/Hz/cell using 12° of tilt, in other words, SDPC working together with downtilt provide a gain of 50 %.

Power efficiency has a similar behavior of spectral efficiency, because it increases for all set of parameters due to cell isolation. Taking a look in Figure 4.22(c), it is evident that the parameters $\Delta_P = 20$ dB and $\Gamma_{min} = -5$ dB provide the highest power efficiency, the gain achieved in this point using downtilt (see Figure 4.22(d)) is 63 % compared without downtilt.

Figure 4.23 shows the total spectral efficiency and power efficiency, when cellular and D2D communications use EPA and SDPC, respectively.

Taking a look in Figure 4.23(a), it is possible to note that spectral efficiency has small variation when the parameters are modified, however, after the eNB changes downtilt to 12° as



(a) Behavior of spectral efficiency applying 0°of tilt.

(b) Behavior of spectral efficiency applying 12°of tilt.

(c) Behavior of power efficiency applying 0°of tilt.

(d) Behavior of power efficiency applying 12°of tilt.

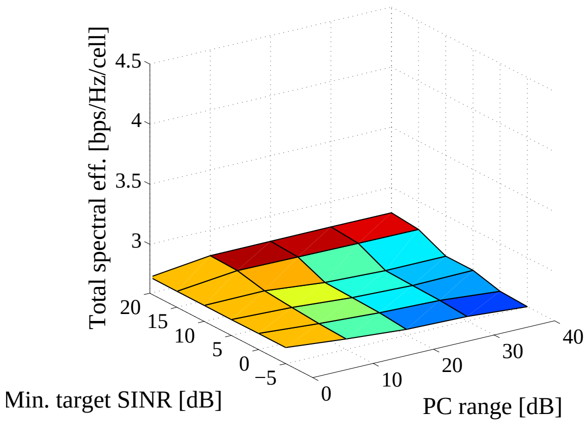
Figure 4.22: Total spectral efficiency and power efficiency (SDPC in cellular and No-PC in D2D links).

shown in Figure 4.23(b), it is possible to check a higher diversity than in the previous results. The highest value of spectral efficiency without downtilt is $2.8\,\mathrm{bps/Hz/cell}$, when $\Delta_P = 40\,\mathrm{dB}$ and $\Gamma_{min} = 20\,\mathrm{dB}$, while using a downtilt angle of $12°$ it is possible to provide $4.4\,\mathrm{bps/Hz/cell/W}$, which represents a gain of $57\,\%$.

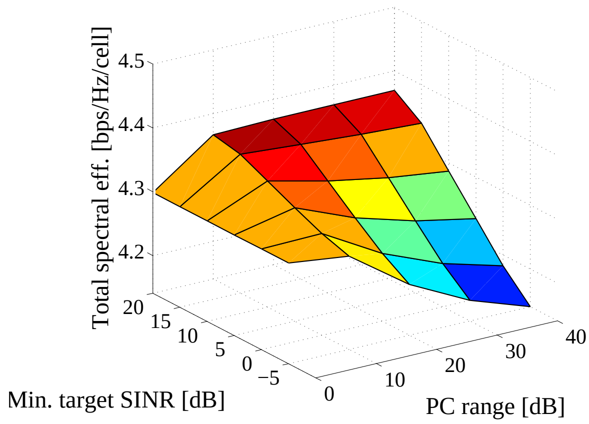
Finally, Figures 4.23(c) and 4.23(d) show how much beneficial is downtilt and SDPC working together. The power efficiency gain reaches $80\,\%$ compared with the case without downtilt, using $\Delta_P = 20\,\mathrm{dB}$ and $\Gamma_{min} = -5\,\mathrm{dB}$. This is a clear evidence that the downtilt decreases inter-cell interference for D2D links. When interference level becomes low due to downtilt, the SDPC decreases the transmit powers, thus increasing energy efficiency.

The Figures 4.22 and 4.23 show that downtilt provides the opportunity of the SDPC to further improve the performance of both communications, since the interference level is reduced due to downtilt, the SDPC can provide high target SINR, while it saves transmit power of eNB and UE achieving a better power efficiency.

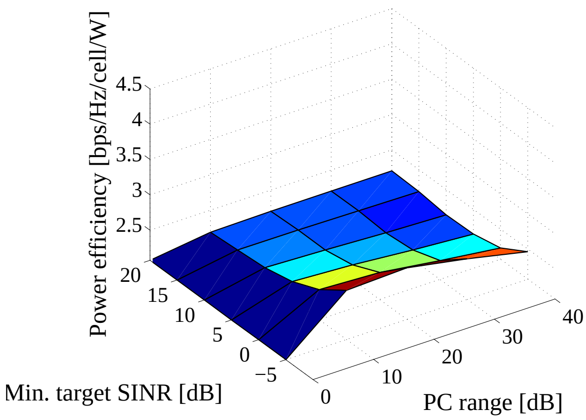
This is indicative that the downtilt working together with the PC schemes can provide high gains of power and spectral efficiency not only in conventional network, but also when D2D communications underlaying cellular networks.



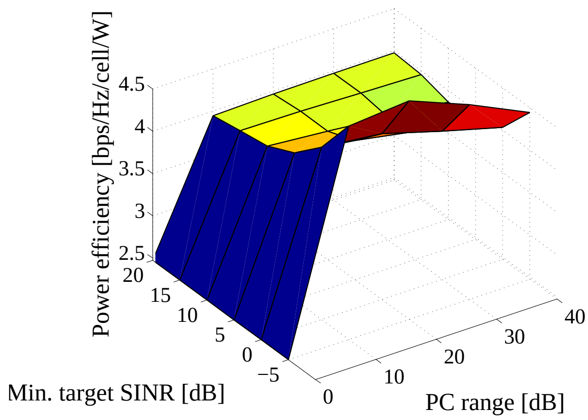
(a) Behavior of spectral efficiency applying 0° of tilt.



(b) Behavior of spectral efficiency applying 12° of tilt.



(c) Behavior of power efficiency applying 0°of tilt.



(d) Behavior of power efficiency applying 12° of tilt.

Figure 4.23: Total spectral efficiency (No-PC in cellular and SDPC in D2D links).

Chapter 5

Conclusions

This master's thesis has dealt with Radio Resource Management (RRM) for cellular and network-assisted Device-to-Device (D2D) communications, as well as strategies used to improve energy efficiency in a scenario where D2D communications underlays the cellular network. Strategies for interference management, such as Power Control (PC) and downtilt have been analyzed and calibrated seeking for the minimum waste of energy in the cellular network without harming its capacity.

This master's thesis addressed the benefits of the Soft Dropping (SD) algorithm for cellular and D2D communications in the Downlink (DL) of a multi-cell scenario through system-level simulations. Results indicate that the SD algorithm in a Micro-cell scenario is effective in controlling the trade-off between system spectral efficiency of cellular communications and power saving of D2D transmitters. The application of SD in D2D communications always provides better performance in terms of total system spectral efficiency and power economy for any operation point than the application of SD to cellular communications. The main reason for that is related with the reduction of the high interference power originated from D2D communications. In DL, D2D transmitters act as interfering sources close to cellular receivers while D2D receivers are far way from both cellular and D2D transmitters. Thus, the SD algorithm appears as a promising solution to protect cellular communications from the interference caused by D2D communications.

PC schemes to protect cellular communications and achieve higher energy efficiency gains for D2D communications on the Uplink (UL) in a Micro-cell scenario were also investigated. Results indicate that in terms of energy efficiency the Soft Dropping Power Control (SDPC) performs better for cellular links while the Open Loop Power Control (OLPC) provides high gains for D2D links. While high values of α have been widely used in OLPC studies, $\alpha \in \{0.4, 0.5\}$ has provided high energy efficiency gains for D2D links. Considering the most favorable scenario for sharing resources in all cells, it was also seen that the minimum cost for enabling system spectral efficiency gains for D2D communications represents a minimal impact of $11\,\%$ on the system spectral efficiency of cellular communications.

Indeed, different PC schemes vary greatly in complexity, numbers of parameters, and have different performance levels. It has been noted that the Equal Power Allocation (EPA) scheme always has the highest spectral efficiency and the lowest power efficiency in both communications. SDPC keeps a reasonable spectral efficiency and provides a gain of $70\,\%$ in power efficiency compared to the Long Term Evolution (LTE) PC schemes for cellular communications. If the purpose of PC is to be power efficient, it would be interesting to use SDPC in cellular communications and OLPC in D2D communications.

We also conclude that for OLPC and Closed Loop Power Control (CLPC), path gain is an important factor affecting performance of the both communication modes and the factor $\sigma = 0.8$ can modify the behavior of CLPC, because it increases the Signal to Interference-plus-Noise Ratio (SINR) of the worst users.

Another conclusion is that Closed Loop Soft Dropping (CLSD), which is based on SDPC and CLPC provides a tradeoff between spectral efficiency and power efficiency, because CLSD has good performance due to knowledge of path gain, current SINR and because it is able to modify the target SINR values. These information are useful to improve spectral and power efficiency of the system, however, the complexity of CLSD and the number of subcarriers used to feedback is higher compared with other PC schemes.

It was shown that algorithms PC schemes are influenced by the load of system. PC schemes such as CLSD provide the best results in terms of total spectral efficiency when the load increases, because it uses the benefits of both CLPC and SDPC, such as feedback and variable target SINR. In terms of power efficiency, EPA shows the worst result to both communications, while SDPC and CLSD provide good results to cellular communications due to explore the diversity. From D2D point of view, OLPC keeps a good performance for all offered loads. This behavior can be explained by the high path gain values due to the proximity of communications inside the hotspot.

In terms of Channel State Information (CSI), we concluded that PC schemes based on many measures suffer a significant loss of spectral and power efficiency when subject to feedback delay. High delays harm the total spectral efficiency and cellular power efficiency, so in this case it should be adopted simple PC schemes to provide the best efficiency to the system. From the D2D point of view, OLPC keeps a good power efficiency independent of the delay, because OLPC provides transmit power based on the metric G (path gain), which does not vary significantly among Transmission Time Intervals (TTIs).

Based on the results of this master's thesis, we concluded that antenna downtilt can be used as a simple and efficient technique not only in conventional cellular networks, but also for D2D communications underlying cellular networks. Regions that offer improved spectral and power efficiency to both types of communication were determined and the range between $8°$ and $12°$ for downtilt angle provided good spectral efficiency to cellular and D2D communications. However, angles between $8°$ and $10°$ are not good parameter values for D2D communications, since they do not lead to power efficiency gains. In this way, angles between $11°$ and $12°$ should be chosen, which provide gains in terms of power efficiency to both cellular and D2D communications that reach $65\,\%$ and $22\,\%$, respectively, while they improved the total spectral efficiency in $58\,\%$.

Downtilt working together with SDPC schemes brings opportunity to reduce inter-cell interference in D2D links due to downtilt and to save transmit power due to SDPC. In other words, downtilt intensifies the gain of SDPC.

This master's thesis intends to contribute to a better understanding of the role and behavior of PC schemes when D2D communications underlay a cellular network.

Appendix A

Proof of convergence SDPC

The target SINR $\Gamma_{k,c,n}(p^{(t)}_{k,c,n})$ of User Equipment (UE) k in the cell c and Physical Resource Block (PRB) n at TTI t is given according to

$$\Gamma_{k,c,n}(p^{(t)}_{k,c,n}) = \begin{cases} \Gamma_{max}, & p^{(t)}_{k,c,n} \leq P_{min}, \\ \Gamma_{max}\left(\dfrac{p^{(t)}_{k,c,n}}{P_{min}}\right)^{\rho}, & P_{min} < p^{(t)}_{k,c,n} < P_{max}, \\ \Gamma_{min}, & p^{(t)}_{k,c,n} \geq P_{max}, \end{cases} \tag{A.1}$$

where

$$\rho = \frac{\log_{10}(\Gamma_{min}/\Gamma_{max})}{\log_{10}(P_{max}/P_{min})}. \tag{A.2}$$

Then, the power per PRB of each UE is updated every transmission as follows

$$p^{(t+1)}_{k,c,n} = p^{(t)}_{k,c,n}\left(\frac{\Gamma_{k,c,n}(p^{(t)}_{k,c,n})}{\gamma_{k,c,n}(\mathbf{p}^{(t)})}\right)^{\beta}, \tag{A.3}$$

By assuming η as the thermal noise at the receiver and $tx(m)$ the transmitter D2D pair $m \in \{0, 1, \ldots, R\}$, the SINR ($\gamma^{(t)}_{k,c,n}$) perceived by of cellular user k in the cell c and PRB n at TTI t can be written as show in Equation (A.4):

$$\gamma^{(t)}_{k,c,n} = \frac{\left|h^{(t)}_{k,c,n}\right|^2 p^{(t)}_{k,c,n}}{\underbrace{\sum_{c'\neq c}^{C}\sum_{k'}^{k}\left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n}}_{\text{Interference from cellular links}} + \underbrace{\sum_{c'}^{C}\sum_{m'}^{M}\left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n}}_{\text{Interference from D2D links}} + \eta^2} \tag{A.4}$$

For power value in $P_{min} < p^{(t)}_{k,c,n} < P_{max}$

$$
\begin{aligned}
I(p^{(t)}_{k,n}) = p^{(t+1)}_{k,c,n} = p^{(t)}_{k,c,n} &\left(\frac{\Gamma_{max}\left(\frac{p^{(t)}_{k,c,n}}{P_{min}}\right)^{\rho}}{\frac{\left|h^{(t)}_{k,c,n}\right|^2 p^{(t)}_{k,c,n}}{\sum\limits_{c'\neq c}^{C}\sum\limits_{k'}^{k}\left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n}+\sum\limits_{c'}^{C}\sum\limits_{m'}^{M}\left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n}+\eta^2}} \right)^{\beta}, \\
= p^{(t)}_{k,c,n} &\left(\frac{\Gamma_{max}\left(\frac{p^{(t)}_{k,c,n}}{P_{min}}\right)^{\rho}\left(\sum\limits_{c'\neq c}^{C}\sum\limits_{k'}^{k}\left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n}+\sum\limits_{c'}^{C}\sum\limits_{m'}^{M}\left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n}+\eta^2\right)}{\left|h^{(t)}_{k,c,n}\right|^2 p^{(t)}_{k,c,n}} \right), \\
= p^{(t)}_{k,c,n}\frac{\left(p^{(t)}_{k,c,n}\right)^{\rho\beta}}{\left(p^{(t)}_{k,c,n}\right)^{\beta}} &\left(\frac{\Gamma_{max}\left(\sum\limits_{c'\neq c}^{C}\sum\limits_{k'}^{k}\left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n}+\sum\limits_{c'}^{C}\sum\limits_{m'}^{M}\left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n}+\eta^2\right)}{\left|h^{(t)}_{k,c,n}\right|^2 P^{\rho}_{min}} \right)^{\beta}, \\
= \left(p^{(t)}_{k,c,n}\right)^{1+\rho\beta-\beta} &\left(\frac{\Gamma_{max}\left(\sum\limits_{c'\neq c}^{C}\sum\limits_{k'}^{k}\left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n}+\sum\limits_{c'}^{C}\sum\limits_{m'}^{M}\left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n}+\eta^2\right)}{\left|h^{(t)}_{k,c,n}\right|^2 P^{\rho}_{min}} \right)^{\beta},
\end{aligned}
\tag{A.5}
$$

Once the all terms in Equation (A.5) are positive, $I(p^{(t)}_{k,n})$ satisfies positivity. To verify monotonicity, it is necessary to ensure that $I(p^{(t)}_{k,c,n}) \geq I(p'^{(t)}_{k,c,n})$, for all $p^{(t)}_{k,c,n} \geq p'^{(t)}_{k,c,n}$, then the value of exponent must be positive.

$$
\begin{aligned}
\left(p^{(t)}_{k,c,n}\right)^{1+\rho\beta-\beta} &\geq \left(p'^{(t)}_{k,c,n}\right)^{1+\rho\beta-\beta}, \\
1+\rho\beta-\beta &\geq 0, \\
1+\beta(\rho-1) &\geq 0, \\
\beta(\rho-1) &\geq -1, \\
\beta(1-\rho) &\leq 1, \\
\beta &\leq \frac{1}{(1-\rho)},
\end{aligned}
\tag{A.6}
$$

To ensure scalability, $aI(p^{(t)}_{k,c,n}) \geq I(ap^{(t)}_{k,c,n})$, for $a \geq 1$. This way

$$
\begin{aligned}
a^1 &\geq a^{1+\rho\beta-\beta}, \\
1 &\geq 1+\rho\beta-\beta, \\
0 &\geq \rho\beta-\beta, \\
\rho\beta-\beta &\leq 0, \\
\rho\beta &\leq \beta, \\
\rho &\leq 1,
\end{aligned}
\tag{A.7}
$$

For power value in $p^{(t)}_{k,c,n} \leq P_{min}$

$$
\begin{aligned}
I(p^{(t)}_{k,n}) = p^{(t+1)}_{k,c,n} = p^{(t)}_{k,c,n} & \left(\frac{\Gamma_{max}}{\frac{\left|h^{(t)}_{k,c,n}\right|^2 p^{(t)}_{k,c,n}}{\sum\limits_{c' \neq c}^{C} \sum\limits_{k'}^{k} \left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n} + \sum\limits_{c'}^{C} \sum\limits_{m'}^{M} \left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n} + \eta^2}} \right)^{\beta}, \\
= p^{(t)}_{k,c,n} & \left(\frac{\Gamma_{max} \left(\sum\limits_{c' \neq c}^{C} \sum\limits_{k'}^{k} \left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n} + \sum\limits_{c'}^{C} \sum\limits_{m'}^{M} \left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n} + \eta^2 \right)}{\left|h^{(t)}_{k,c,n}\right|^2 p^{(t)}_{k,c,n}} \right)^{\beta}, \\
= \left(p^{(t)}_{k,c,n}\right)^{1-\beta} & \left(\frac{\Gamma_{max} \left(\sum\limits_{c' \neq c}^{C} \sum\limits_{k'}^{k} \left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n} + \sum\limits_{c'}^{C} \sum\limits_{m'}^{M} \left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n} + \eta^2 \right)}{\left|h^{(t)}_{k,c,n}\right|^2} \right)^{\beta}, \\
= \left(p^{(t)}_{k,c,n}\right)^{1-\beta} & \left(\frac{\Gamma_{max} \left(\sum\limits_{c' \neq c}^{C} \sum\limits_{k'}^{k} \left|h^{(t)}_{k,c',n}\right|^2 p^{(t)}_{k',c',n} + \sum\limits_{c'}^{C} \sum\limits_{m'}^{M} \left|h^{(t)}_{k,tx(m'),c',n}\right|^2 p^{(t)}_{tx(m'),c',n} + \eta^2 \right)}{\left|h^{(t)}_{k,c,n}\right|^2} \right)^{\beta},
\end{aligned}
\tag{A.8}
$$

Once the all terms in Equation (A.8) are positive, $I(p^{(t)}_{k,n})$ satisfies positivity. To verify monotonicity, it is necessary to ensure that $I(p^{(t)}_{k,c,n}) \geq I({p'}^{(t)}_{k,c,n})$, for all $p^{(t)}_{k,c,n} \geq {p'}^{(t)}_{k,c,n}$, then the value of exponent must be positive.

$$
\begin{aligned}
\left(p^{(t)}_{k,c,n}\right)^{1-\beta} &\geq \left(p^{(t)}_{k,c,n}\right)^{1-\beta}, \\
1 - \beta &\geq 0, \\
1 &\geq \beta, \\
\beta &\leq 1,
\end{aligned}
\tag{A.9}
$$

To ensure scalability, $aI(p^{(t)}_{k,c,n}) \geq I(ap^{(t)}_{k,c,n})$, for $a \geq 1$. This way

$$
\begin{aligned}
a^1 &\geq a^{1-\beta}, \\
1 &\geq 1 - \beta, \\
\beta &\geq 0,
\end{aligned}
\tag{A.10}
$$

The main relations are defined below:

$$\rho \leq 1, \tag{A.11}$$

$$\beta \leq \frac{1}{(1-\rho)}, \tag{A.12}$$

$$\beta \leq 1, \tag{A.13}$$

$$\beta \geq 0, \tag{A.14}$$

Finally, we can combining them

$$-\infty \leq \rho \leq 0, \tag{A.15}$$

$$0 \leq \beta \leq \frac{1}{(1-\rho)}, \tag{A.16}$$

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