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Hybrid Power Control for LTE Uplink

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Summary

One of the main methods for handling interference and managing the radio resources in communication systems is power control. The conventional power control techniques used in LTE have some limitations. In this thesis, the Hybrid power control (HPC) technique has been introduced in order to overcome these limitations.

Power control in LTE has a major role in the management of connectivity, interference, and energy consumption. Because of the importance of power control, most part of this thesis is dedicated to study the conventional power control in detail. In Chap. 2, the power control equation as described in the standard is explained in detail highlighting the most relevant parameters, such as the pathloss compensation factor component and the feedback component. Later, the two main power control techniques, i.e. open loop power control and closed loop power control, are described and commented.

In Chapt. 3, we present the numerical results for open and closed loop techniques, obtained for a seven cells scenario and the WIM (WINNER phase 2) channel model. At the beginning, the simulations have been done for the open loop power control, studying its behavior under different circumstances, different scheduling strategies, and targeting different data rates. Then, the fractional open loop power control has been tested and, finally, system performance for open and fractional controls has been reevaluated for different traffic levels.

Then performance of closed loop power control has been evaluated for different values of traffic, different scheduling strategies, and targeting different data rates. By doing an exhaustive search using all the possible combinations for the different power control parameters, the maximum possible achievable rate at different traffic values for open loop power control and closed loop power control was selected and compared. The same search and comparison have been done after changing the cell radius with several number of users and cell radius.

In the final part of Chapt. 3, the effect of changing the target SINR on the achieved rate and consumed power is studied and plotted for both open loop power control and closed loop power control; different control power control parameters and different traffic levels have been used for completing the simulation results. In fact, changing the target signal to interference plus noise ratio (SINR) changes the transmitted power and consequently the interference power, the received power, and the achieved data rate.

We noticed that the difference in performance between the open loop power control and the closed loop power control is not so significant in the considered system. Furthermore, both of these conventional power control techniques have some limitations. Therefore, a hybrid approach, denoted as Hybrid Power Control (HPC), has been introduced to overcome these limitations (Chapt. 4). The HPC was designed according to the idea that users within the cell can be divided into two or more groups; each group is selected according to pathloss w.r.t serving eNB. The members of these groups share, more or less, the same capabilities, achievable rate and vulnerability to interference. Each group has a different SINRtarget and a different maximum achievable rate regardless of their maximum allowed power. If the system is divided into two groups a cell edge (CE) users group, and a cell center (CC) users group can be defined. CE users' have a rate limit, trying to achieve a higher rate by using more power (or equivalently SINRtarget) and this will lead to a power waste and an increase of interference without any additional gain. In short, the HPC is a technique which uses a different SINRtarget and, most likely, a different power control mechanism for each cell group, i.e. open (OLPC) for CC users and closed (CLPC) for CE users.

After introducing the HPC and justifying its assumptions and the theory behind it, HPC performance was evaluated and analyzed using both mathematical formulation and simulations (Chapt. 4 and 5). We have seen that the HPC can achieve an improvement in the average cell rate around 23% w.r.t. conventional techniques. Moreover, the average transmitted power is reduced by more than 22 dB. Furthermore, the CE users' performance is good and controllable in a flexible way. The energy efficiency for the HPC was also evaluated and compared against that of the conventional power control techniques in order to clarify its advantages.

The main innovative contributions of this thesis can be summarized in the following list:

1- The hybrid power control approach, mainly constituted by using two different power control techniques for two parts of the cell. We chose OLPC for central area (CC) and CLPC for cell edge (CE). From our point of view, and verified through extensive simulations, this is the most suitable combination for satisfying the users requirements.
2- Optimal $SINR_{target}$ have been selected for each part of the cell. The choice is based on our conjecture that each part of the cell has a maximum, different, $SINR_{target}$, which should not be exceeded. For the CE this optimum $SINR_{target}$ is lower than that of CC. In fact choosing a higher $SINR_{target}$ for CE users, regardless of the existence of any CC users, will lead to an increase of the interference and of the consumed power.
3- Search
4- of the optimum pathloss that splits the cell into CC and CE. This splitting pathloss was found using also an analytical method. Using our method, a general splitting point can be found iteratively, regardless the position of the

users. Then, we suggest also splitting the cell into more than two groups, in order to achieve the full potential of each user in the cell, while keeping the interference at minimum. We report an example of cell splitting into four groups and the optimum $SINR_{target}$ for each group.

Sommario

Uno dei principali metodi di gestione dell’interferenza e delle risorse radio nei sistemi di comunicazione è il controllo di potenza. Le tecniche di controllo di potenza convenzionali utilizzati in LTE hanno alcune limitazioni. In questa tesi, la tecnica di controllo di potenza ibrida (Hybrid Power Control) è stata introdotta per superare queste limitazioni.

Il controllo della potenza in LTE ha un ruolo importante nella gestione di connettività, interferenza, e il consumo di energia. Data l'importanza del controllo di potenza, la parte iniziale di questa tesi (Cap. 2) è dedicata allo studio del controllo di potenza convenzionale in dettaglio; all'inizio l'equazione di controllo di potenza come descritta nello standard è spiegata in dettaglio evidenziando i parametri più importanti, come la perdita di percorso, il fattore di compensazione e la componente feedback. In seguito, le due principali tecniche di controllo di potenza, vale a dire il controllo di potenza ad anello aperto e il controllo di potenza ad anello chiuso, sono state analizzate in dettaglio.

Nel cap. 3, una estesa campagna di simulazioni è stata effettuata in MATLAB su uno scenario di sette celle e usando il modello di canale WIM (WINNER phase 2). All'inizio, la simulazione è stata fatta per il controllo della potenza ad anello aperto, studiando il suo comportamento in diverse circostanze, per diverse stratigie di pianificazione, e diverse velocità di trasferimento dati. Successivamente, il controllo della potenza frazionata ad anello aperto è stato testato e le prestazioni per il controllo frazionato e non valutate nuovamente per diversi valori di traffico.

Il controllo di potenza ad anello chiuso è stato poi considerato in termini di prestazioni, valutate per diversi valori di traffico, diverse strategie di pianificazione e diverse velocità di trasferimento dati. Facendo una ricerca esaustiva sulle possibili combinazioni dei vari parametri di controllo di potenza, la

velocità massima possibile realizzabile per valori di traffico differenti e per il controllo di potenza ad anello aperto e anello chiuso è stata selezionata e comparata. La stessa ricerca e lo stesso tipo di confronto sono stati fatti per diversi raggi di cella e numeri di utenti.

Nella parte finale del cap. 3, è stato studiato l'effetto della modifica del rapporto SINR sulla velocità dati raggiunta e sulla potenza consumata sia per il controllo di potenza ad anello aperto che per il controllo di potenza ad anello chiuso. Cambiare infatti il rapporto SINR desiderato comporta un cambiamento nella potenza trasmessa e coneguentemente nell'interferenza, e nella velocità di trasmissione dati.

Abbiamo notato che la differenza di prestazioni tra il controllo di potenza ad anello aperto e il controllo di potenza ad anello chiuso non è così rilevante nel sistema introdotto. Inoltre, entrambe queste tecniche di controllo di potenza convenzionali hanno delle limitazioni. Quindi abbiamo introdotto una tecnica ibrida (HPC) per superare queste limitazioni (Cap. 4). L'HPC è stato progettato sulla base della percezione che gli utenti all'interno della cella possono essere divisi in due o più gruppi; ogni gruppo è selezionato in base alla perdita di percorso rispetto alla stazione base. I membri di ognuno di questi gruppi condividono, più o meno, le stesse capacità, il tasso realizzabile e la vulnerabilità alle interferenze. Ogni gruppo ha un SINR di riferimento diverso e un tasso massimo raggiungibile diverso, indipendentemente dalla loro potenza massima consentita. Se il sistema è diviso in due gruppi, uno a bordo cella (CE), e uno a centro cella (CC) possiamo osservare che gli utenti CE avranno un limite di velocità e ogni tentativo di superarlo porterà a uno spreco di potenza e a un aumento di interferenza senza ulteriore guadagno. In breve, l'HPC è una tecnica che utilizza un SINR obiettivo diverso e un meccanismo di controllo di potenza diverso per ogni gruppo, ovvero aperto (OLPC) per CC e chiuso (CLPC) per CE.

Dopo aver introdotto l'HPC e giustificato le sue ipotesi e la teoria sottostante, le prestazioni dell'HPC sono state valutate e analizzate utilizzando sia la formulazione matematica che la simulazione (Cap. 4 e 5). Si è visto che l'HPC può ottenere un miglioramento nella velocità di trasmissione della cella mediamente pari a circa il 23%. Inoltre, la potenza media trasmessa è ridotta di oltre 22 dB. Infine le prestazioni degli utenti CE sono accettabili e controllabili con flessibilità. Nella parte finale del cap. 5, l'efficienza energetica dell'HPC è stata valutata e confrontata con quella delle tecniche di controllo di potenza convenzionali per chiarire ulteriormente i suoi vantaggi.

I principali contributi innovativi di questa tesi possono essere riassunti nel seguente elenco:

1- Introduzione dell’approccio ibrido, costituito dall’utilizzo di due diverse tecniche di controllo di potenza per ogni parte della cella. Abbiamo scelto OLPC per la parte centrale (CC) e CLPC per il bordo (CE). Dal nostro punto di vista, e in base a verifiche simulative, questa è la combinazione più adatta per le esigenze degli utenti.

2- Il SINRtarget ottimale è stato selezionato per ogni parte della cella. La scelta è basata sull’idea che ogni parte della cella ha un proprio massimo SINRtarget, che non deve essere superato. Per la CE, questo SINRtarget ottimale è inferiore a quello del CC. Scegliere un SINRtarget maggiore per gli utenti CE, indipendentemente dall'esistenza di eventuali utenti CC, porta ad un aumento dell'interferenza e della potenza consumata.

3- E’ stato calcolata la perdita di percorso ottimale che divide la cella in CC e CE. Questa perdita di percorso è stata trovata utilizzando un metodo analitico. Usando il nostro metodo, un punto di divisione generale può essere trovato iterativamente, indipendentemente dalla posizione degli utenti. In genere, si consiglia di dividere la cella in più di due gruppi, al fine di raggiungere il pieno potenziale di ciascun utente nella cella, mantenendo l'interferenza al minimo. Abbiamo fornito un esempio di divisione della cella in quattro gruppi e il SINRtarget ottimale è stato trovato per ogni gruppo.

Acknowledgement

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Chapter 1

Introduction to LTE

Long term evolution (LTE) was developed by the 3G partnership project (3GPP) in order to fulfill the growing demand in traffic. This standard for new access technology aims to achieve higher data rates, and spectral efficiency than that of the current HSPA [1]. The evolution of just the radio interface was not enough, since there was a goal to have a packet-optimized system; for this reason and others also the system architecture needed to be evolved and the new system architecture evolution (SAE) started after the development of the access part [2].

In short, LTE or the Evolved Universal Terrestrial Access Network (E-UTRAN) is the access part and one of two parts of the Evolved packet system (EPS), which is designed to fulfill the current need for high speed data transmission. EPS is composed of two components, the first component is LTE, and the second component is the SAE and its Evolved Packet Core (EPC). EPS is a packet-only system and, consequently, has internet protocol (IP) traffic. In fact, all types of traffic are carried over IP [3].

In order to achieve this high performance, LTE employs technologies such as orthogonal frequency division multiplexing (OFDM) and multi antenna transmission. In addition LTE achieves high spectral efficiency using link adaptation and frequency domain scheduling. According to all these features, LTE is characterized by high spectrum flexibility.

LTE uses OFDM, as already mentioned, i.e. a multicarrier transmission technique. In OFDM data is transmitted over narrow band orthogonal subcarriers, with subcarrier spacing Δf = 15KHz. OFDM has several attractive characteristics, among which:

- High spectral efficiency
- The possibility of using FFT/IFFT blocks (digital implementation)
- Channel equalization can be done by using a cyclic prefix (CP)
- Flexibility in assigning resources, based on subcarriers, and setting the modulation and coding scheme for each subcarrier according to channel quality.

1.1 Structure of physical resources:

The LTE supports both frequency division duplexing (FDD) and time division duplexing (TDD) for Downlink (DL) and Uplink (UL) transmission. Radio frame of LTE is 10ms long and it contains 10 sub frames, each of 1ms. A sub frame consists of two consecutive time slots, each of 0.5 ms duration, as shown in Fig. 1.1. Each slot comprises a set of OFDM subcarriers and the number of subcarriers per slot is decided according to the desired transmission bandwidth.

There can be seven or six OFDM symbols per slot according to the cyclic prefix length. Seven symbols per slot is used in case of normal length cyclic prefix, and six symbols per slot is used in case of extended length cyclic prefix, which is used in case of extensive delay spread, and in case of Multimedia Broadcast Single Frequency network (MBFSN) based multicast/broadcast transmission [5, 6].

The smallest resource unit is called the resource element (RE), where each RE comprises one subcarrier in the frequency domain and one OFDM symbol in the time domain. In the frequency domain subcarriers are grouped into resource blocks (RBs). RB is the smallest resource allocation element a scheduler can assign to a user. Each RB consists of 12 subcarriers with 15 KHz of spacing, corresponding to a bandwidth equal to 180 KHz. So one RB consists of 84 REs when using normal length cyclic prefix, and 72 REs in case of extended length cyclic prefix [4, 5]. It can be seen that the physical resources create a time-frequency resource grid, as shown in Fig. 1.2.

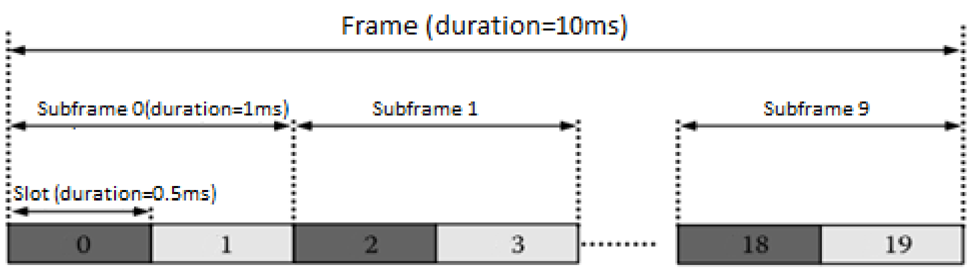


Fig. 1.1 LTE sub-frame structure

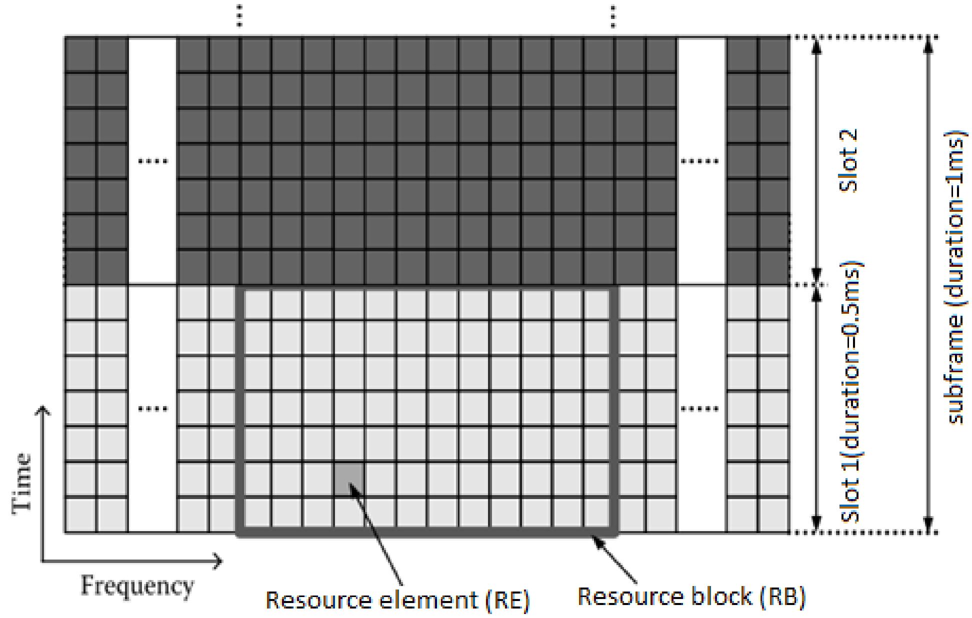


Fig. 1.2 LTE resource grid

1.2 Transmission schemes

The characteristics and the capabilities, e.g. available transmission power, of the evolved node B (eNB) and of the user equipment (UE) are different. Therefore, there are some differences between the Downlink physical layer and the Uplink physical layer.

In the Downlink, orthogonal frequency division multiple access (OFDMA) is used, which is an extension of OFDM and inherits its robustness to multipath fading. The subcarriers are divided into number of subsets (i.e. channels) and assigned to users. Multiuser diversity can be employed by assigning the channel to the user with the best channel gain.

One of the main disadvantages of the OFDMA is the high peak to average power ratio (PAPR), hence highly linear amplifier should be used, which has low energy efficiency and high power consumption. Since the capabilities of the UE are lower than those of eNB, especially in terms of available transmission power, the LTE Uplink uses single carrier frequency division multiple access (SC-FDMA).

SC-FDMA is a modified version of OFDM, mainly based on DFT pre-coded OFDM, where symbols are transmitted serially and occupying all the bandwidth. SC-FDMA and OFDMA have a lot of similarities between them: The transmitter and receiver of both are very similar, as illustrated in Fig. 1.3: frequency domain equalization is done by adding guard times in both schemes, and both achieve almost the same performance and flexibility levels. However, the SC-FDMA has lower PAPR [4] than OFDMA, which makes it more suited to the Uplink. The difference between sub-carriers assignment in OFDMA and in SC-FDMA is illustrated in Fig. 1.4.

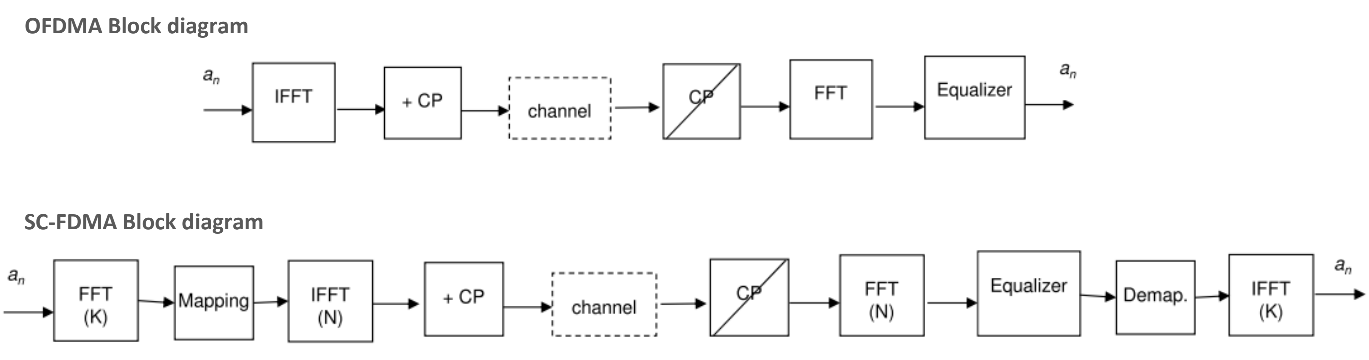


Fig. 1.3 OFDMA and SC-FDMA block diagrams.

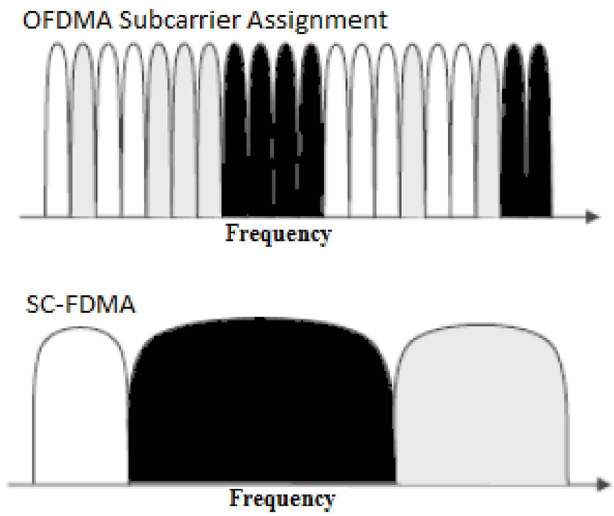


Fig. 1.4 OFDMA and SC-FDMA sub-carrier assignment in frequency domain.

1.3 Scheduling in LTE

Scheduling is the process of allocating radio resources to different users, trying not to violate some requirements, e.g. fairness and quality of service, and, at the same time, achieve efficient resource utilization [5]. The station eNB controls scheduling (resource assignment) for both downlink and uplink (uplink scheduling is done in the eNB to maintain orthogonality between different terminals in the same cell) [4].

In LTE there is the possibility of Channel dependent scheduling. Channel dependent scheduling is important because it exploits the channel quality, and achieves efficient radio resources utilization. Hence, the UE is scheduled based on the channel quality and binding traffic in the UE's transmission buffer. Scheduling can be done in both time and frequency domain.

Scheduler assign resources every 1ms (sub frame duration). Assignment is done on the basis of RB pairs (one RB occupies 180 kHz in the frequency domain). The scheduled RBs are signaled to the UE over the physical downlink control channel (PDCCH).

There is also a semi persistent scheduling in LTE. In semi persistent scheduling, resources are assigned ahead of time in a semi-static way, leading to reduction in the PDCCH overhead. This type of scheduling is suitable for applications which may have predicted/periodic data generation such as VOIP [6].

In the uplink, the assigned RBs to a particular UE have to be adjacent to maintain the single carrier property, which leads to a limitation in the efficiency of utilization of frequency selective scheduling.

1.4 LTE channels

There are three types of channels in LTE. These channels are used to transport data and control signals between different layers of the LTE radio architecture. These three types are transport channels, logical channels, and physical channels.

Logical channels are used by the medium access control (MAC) to offer service to radio link control (RLC) [2]. Logical channels characterize the type of data to be transmitted [2]. Logical channels can be divided into either traffic channels or control channels.

Transport channels work as interface between the physical layer and MAC layer [2]. Some examples of the transport channels are the Broadcast Channel (BCH), Downlink Shared Channel (DL-SCH), and Uplink Shared Channel (UL-SCH). Each transport channel is mapped to the related physical channel.

Physical channels carry user’s data and control data over the radio interface. Each physical channel undergoes some defined procedures before transmission, such as scrambling, modulation, mapping, etc. Different physical channels and their role are shown in Table 1.1.

Channel	Description	Role
PDSCH	Physical downlink shared channel	Carries downlink user data from upper layers as well as paging signaling (DL)
PMCH	Physical multicast channel	Used to support point-to-multipoint multimedia broadcast multicast service (MBMS) traffic (DL)
PBCH	Physical broadcast channel	Used to broadcast a certain set of cell or system-specific information (DL)
PCFICH	Physical control format indicator channel	Determines the number of OFDM symbols used for the allocation of control channels (PDCCH) in a sub frame (DL)
PDCCH	Physical downlink control channel	Carries scheduling assignments, uplink grants, and other control information; the PDCCH is mapped onto resource elements in up to the first three OFDM symbols in the first slot of a sub frame (DL)
PHICH	Physical HARQ indicator channel	Carries the hybrid automatic repeat request (HARQ) ACK/NAK (DL)
PUSCH	Physical uplink shared channel	Carries uplink user data from upper layers; resources for the PUSCH are allocated on a sub frame basis by the scheduler (UL)
PUCCH	Physical uplink control channel	PUCCH carries uplink control information, including channel quality indication (CQI), HARQ ACK/NACK, and uplink scheduling requests (UL)
PRACH	Physical random access channel	Used to request a connection setup in the uplink (UL)

Table 1.1 Different physical channels and their description

1.5 Channel quality

Channel state information (CSI) is used to provide the eNB with the channel information, which allows the eNB to take smart decisions. These information about the channel state are used for packet scheduling, and for choosing the modulation and coding scheme.

Channel state information comprises three indicators sent by the UE: rank indicator (RI), pre coding matrix indicator (PMI), and channel quality indicator (CQI). CQI is the most important one from the scheduling and link adaptation point of view [8].

From scheduling point of view, the UE is selected according to its channel quality and consequently the channel quality has to be estimated. In addition to that, the LTE employs link adaptation. Link adaptation is a technique that gives the UE a rate according to its channel quality. Link adaptation is based on AMC (adaptive modulation and coding): AMC gives the UE the modulation and coding scheme with max data rate at block error rate not exceeding 10%, and the selection process is based on the received SINR, namely the received channel quality feedback [9].

CQI feedback indicates the data rate which can be supported by the channel, taking into account the SINR and the characteristics of the UE's receiver. The eNB uses the CQI to select the modulation and coding scheme (MCS) according to the channel condition [10]. There are 16 MCS-CQI pairs which are given in Table 1.2.

The CQI has some important properties that affect the LTE system performance. Some of them are:

- CQI is derived from the estimated SINR, signal quality, based on the measurements of reference signals.

- CQI reporting, in downlink, can be periodic and, in that case, it is sent over PUCCH; it can also be aperiodic and sent over PUSCH.
- The types of CQI reporting are wide band CQI, UE-selected sub band, and eNB configured.

In the downlink, the UE estimates the channel state from downlink transmitted reference symbols, and then the channel state information is sent over the PUCCH or PUSCH. Channel state is under control of the eNB, the UE cannot send the channel state information without the eNB knowledge.

In the uplink, the channel state information of the uplink is calculated using the sounding reference signals (SRS). SRS is a type of reference signal which is mainly used for channel estimation in the uplink, allowing smart scheduling as well as link adaptation. The SRS provide the channel state over the all bandwidth, which allow the eNB to take the smart decisions regarding resource allocation and link adaptation. The rate at which the SRS is transmitted is provided by the eNB [4].

CQI Index	Modulation	Code Rate X 1024	Efficiency
0	No transmission		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

Table 1.2 CQI values and their corresponding modulation and coding schemes

1.6 Power control

The LTE radio channel is characterized by interference and multipath propagation, e.g. pathloss and fading, which will affect the received signal quality. Hence, in order to achieve a good network performance a power control mechanism must be used to fulfill the quality of service (QOS) and SINR requirements without causing large interference.

Uplink power control in LTE is considered very important, because of UE's limited power and also the interference in the Uplink changes over time with the scheduling decisions. That is why uplink power control is studied in great detail. Uplink power control in LTE comprises an open loop power control and a closed loop power control, which are used to handle the slow and fast channel variations as well as the interference. LTE, also, supports fractional pathloss compensation, which reduces the transmission power of users and, as a result, the generated interference [4, 5].

In the LTE downlink direction, power control is generally not used. Instead, smart scheduling and link adaptation based on rate control as well as other interference mitigation techniques can be used. Some of the most investigated techniques based on inter-cell coordination are:

- Network MIMO
- Adaptive fractional frequency reuse
- Opportunistic and organized inter-base station access

1.7 Inter cell interference coordination

Inter cell interference coordination (ICIC) is used to keep inter-cell interference under control by measuring the radio resources. The ICIC takes into account the state of radio resources and traffic for multiple cells.

The primary approach adopted in LTE for ICIC is frequency domain coordination of RB allocation between cells to avoid collision. ICIC signaling is sent over (X2) interface. X2 is the interface that is used for inter-connecting the eNBs within the E-UTRAN [4]. There are two types of information exchanged over the X2 interface:

1. Information regarding the interference,
2. Information regarding the handover.

There are two indicators exchanged between eNBs in the uplink ICIC, the high interference indicator (HII) and overload indicator (OI). The high interference indicator informs the other cell about which part of the bandwidth will be scheduled to the cell edge users. The over load indicator provides information to the neighboring cells about the experienced uplink interference level [4, 7].

An enhanced version of the inter cell interference coordination (eICIC) has been introduced in LTE release 10, mainly to address interference in case of heterogeneous networks. The major change is the addition of time domain ICIC, which is realized through almost blank sub frame (ABS).

In this chapter we have given a brief introduction about some of the important aspects of LTE. The rest of the thesis is structured as follows. Introduction of power control and its main parameters and techniques is given in chapter 2. Chapter 3 contains a comprehensive analysis and simulations of power control and its techniques. Introducing and testing the Hybrid power control is provided in Chapter 4.

Chapter 2

Power control in LTE

Power control is used to set the transmitted power in order to achieve a desired data rate. Setting the transmitted power is not something arbitrary since using too much transmission power clearly leads to high inter-cell interference, and using too little transmission power leads to low throughput. Hence, a suitable transmission power value should be set.

LTE uplink uses an orthogonal scheme, SC-FDMA, which allows multiplexing different users within the same cell without having problems such as near far effect or intra-cell interference [12, 13]. Regardless the orthogonality of SC-FDMA, which limits intra-cell interference, there is still the problem of inter-cell interference as, in general, LTE uses frequency reuse 1, and high interference levels from other cells' UEs can limit the uplink coverage if the power of those interfering UEs is not controlled [7].

Power control is also used to improve the power consumption efficiency since cell phones and portable devices have a limited amount of available power. Furthermore, currently the research is shifting towards using sustainable energy, which does not only focus on the source of the energy, but also on the energy efficiency of the devices [13].

From all these considerations, it can be observed that power control is setting the transmission power in order to improve system capacity, coverage, user quality, and to reduce power consumption.

LTE uses a combination of open loop and closed loop power control [1, 4, and 5]. Open loop is based on pathloss estimation. Closed loop is a faster adaptation which is used to control interference and tune the power setting to adapt to the channel conditions with more precision.

Uplink power control is applied to different uplink channels. Specifically, in the LTE standard, the power control equations are given for the PUSCH and PUCCH, as well as the SRS. The power control equations are, in general, composed of the summation of static, or semi-static, parameters and a dynamically updated offset.

Starting from LTE release 10, PUSCH and PUCCH can be simultaneously transmitted over the same or different component carriers. The power control guarantees that the total UE transmission power is less than or equal the maximum terminal output power P_{max}. As a result, if PUCCH is going to be transmitted along with PUSCH, first the power is assigned to the PUCCH to ensure a reliable transmission for the control signaling, then the remaining power becomes available for the PUSCH [1].

The requirement of PUCCH power control is straightforward, just to reach a certain decoding error rate, usually low, of the control information [5]. In fact it is not required to reach a maximum data rate and different users' PUCCH transmissions are code division multiplexed. Hence, in order to facilitate a good control of interference among users, the pathloss must be always fully compensated in PUCCH [5].

When adjusting the PUCCH transmission power, it should be noted that there are different PUCCH formats, each of them carrying different control information, and each of them having a different error rate and SINR requirements. Hence, each of them should have a different power setting, which is tuned according to a format parameter.

Power control for SRS follows PUSCH power control. The difference between PUSCH power control and SRS power control is that, in the PUSCH power control, the power is distributed over the bandwidth occupied by PUSCH. However, in the SRS power control the bandwidth occupied by the SRS is the one that is compensated, instead of the PUSCH bandwidth. Also an additional power offset is added in the SRS power control [4].

For the PUSCH power control it should be taken in mind that, in general, it is desired to have a high capacity and coverage in the served cells. Since LTE was introduced to cope with the ever increasing need for high speed data transmission. Hence, the role of power control in PUSCH becomes decisive to achieve these requirements. That is why a detailed explanation of the power control and the power control equation for PUSCH is going to be provided.

2.1 Power control for PUSCH

PUSCH carries the user data and control information for active users, which makes it important to be optimized. Power control in PUSCH aims to achieve a desired rate along with controlled interference on other cells users.

The transmit power of PUSCH is first scaled by the ratio of the number of antennas ports with a non-zero PUSCH transmission to the number of configured antenna ports for the transmission scheme. The resulting scaled power is then split equally across the antenna ports on which the non-zero PUSCH is transmitted [11].

2.1.1 Power control equation

The transmission power for the PUSCH channel is defined by the following equation [11]:

$$\mathrm{P_{PUSCH}} = \min\{P_{max} - P_{PUCCH}\,, P_0 + \alpha PL_{DL} + 10\log_{10}(M) + \Delta_{MCS} + f(\Delta_{TPC})\}\ [\mathrm{dBm}] \quad (2.1)$$

where

- P_{max}: the max transmission power of the UE.

- P_{PUCCH}: transmission power allocated for the PUCCH.

- $P_{max} - P_{PUCCH}$: transmission power available for PUSCH after assigning the PUCCH transmission power on the carrier. This indicates PUCCH priority over PUSCH.

- P_0 : a parameter broadcasted, which reflects the desired target received power. It depends on the noise and interference levels.

- PL_{DL}: downlink pathloss estimated by the UE.

- α: fractional pathloss compensation factor. It controls how much of the pathloss is compensated. It allows tradeoff between uplink capacity and cell edge bit rate. The parameter α takes the values {0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1}.

- M: the number of RBs allocated to the user.

- Δ_{MCS}: MCS dependent component (also known as Δ_{Tf}, TF is the transport format). It allows changing the power according to the transmitted data rate.

In LTE release 10 Δ_{MCS} doesn't work with PUSCH transmission mode 2.

It can be treated as a power control command used by the eNB. The eNB changes the MCS used by the UE then send Δ_{MCS} to change the transmission power. Δ_{MCS} is characterized by the following properties:

- It can be set to zero if not needed, for example if fast adaptive modulation and coding (AMC) is used [4].
- It should be disabled in case of fractional pathloss compensation [4].
- The higher the coding rate and modulation order, the higher the Δ_{MCS}. And the transmission power is increased.

- $f(\Delta_{TPC})$: Power control adjustment term (responsible for the closed loop PC)

- Δ_{TPC}: Correction value known as the transmission power control (TPC) command. These commands can be accumulative or absolute.

For the accumulative TPC commands, each command is a power step relative to the previous power adjustment level value. The update equation is $f(i) = f(i-1) + \Delta_{TPC}(i-4)$, $f(0) = 0$. (2.2)

The accumulative TPC commands are suitable for fine tuning of the transmission power. There are two set of available steps: {-1, 1} dB, and {-1, 0, +1, +3} dB.

The absolute TPC commands are independent of the sequence of the TPC commands that may have been received previously. The set of offsets signaled by the TPC commands is {-4, -1, +1, +4} dB. The update equation is

$$f(i) = \Delta_{TPC}(i-4). \qquad (2.3)$$

The absolute TPC commands are suitable when the scheduling of the UE is not continuous, due to the nature of data generation or other factors, but it keeps stopping and starting.

The power control commands are included in the uplink scheduling grants, and, also, they can be provided on a special PDCCH that provides the power control commands to multiple UEs simultaneously [5].

It has been illustrated that the power control in the uplink is adjusted using a set of specific parameters. It is worth noting that some of these parameters are sent from the eNB to the UE and these parameters are $\{P_0, \alpha, \Delta_{MCS}$, and $\Delta_{TPC}\}$. On the other side, the pathloss estimate (PL) is calculated by the UE. Fig. 2.1 shows how each power control parameter is obtained.

It should also be noted that, during data transmission, the used P_{PUSCH} depends on signal strength measurements. There are two types of signal strength measurements: measurements done by the UE itself, which are used to calculate the PL estimate and these measurements are sufficient in case of open loop power control. Additional measurements, for the closed loop power control, are done by the eNB. These measurements are used to decide the correct TPC command to be transmitted from the eNB to the UE in order to adjust its power [14].

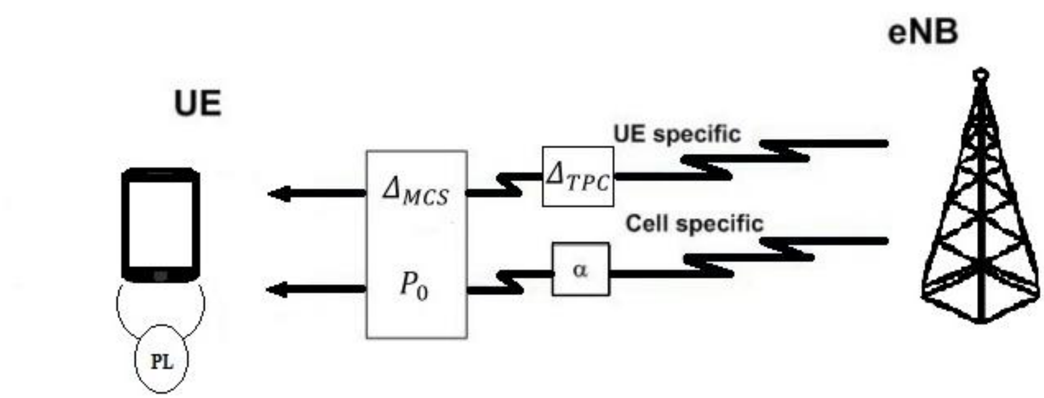


Fig. 2.1 How the power control parameters for PUSCH are obtained

2.1.2 Fractional pathloss compensation

One of the ways to contrast interference in the uplink power control is the fractional pathloss compensation, which is used in the open loop power control. Here the UE sets the transmitted power according to its own measurements for the pathloss, and uses the pathloss compensation factor (α) detected by the network and provided by the eNB. By doing that, the received SINR depends on the users' pathloss. The more the pathloss, moving toward the cell edge, the lower the increase rate of the UE transmit power, and the lower the received SINR as well as the inter cell interference [12 - 14].

Using fractional pathloss compensation leads to receiving different values of power for different users according to their pathloss value and channel conditions. On the other side, by using full pathloss compensation the pathloss difference between users is not important anymore, since it is fully compensated.

2.1.3 Power spectral density

As the number of the assigned RBs to a UE changes, according to bandwidth allocation, the value of the transmitted power changes as well. Thus the power control in LTE does not set the value of transmitted power, but it controls the transmitted power spectral density (PSD). The PSD is the power assigned to the UE per RB; at the same time it must be taken into account that the total transmission power of the UE, summation of all the UE RBs assigned powers, should not exceed the UE max transmission power.

Since each RB assigned to a UE has the same amount of power [4, 14], We can remove the term $[10\log_{10}(M)]$ from equation (2.1) to calculate the power per RB, and, neglecting the other feedback components such as the $\{\Delta_{MCS}$, andΔ_{TPC}}, the open loop components of the power control in LTE are expressed by the PSD:

$$PSD_{Tx} = P_0 + \alpha PL_{DL} \text{ [dBm/RB]}, \quad (2.4)$$

$$PSD_{Rx} = P_0 + \alpha PL_{DL} - PL \text{ [dBm/RB]}. \quad (2.5)$$

2.2 Strategies for power control

There are several strategies for the power control and each one of these strategies uses different value of α, which means that each one of them handles pathloss compensation in a different way. This also implies that the values of the received PSD, and the generated interference will be different. Therefore they will affect the achieved data rate and system performance differently. The following 4 strategies can be divided into open loop ones (the first 3, described in Sect. 2.2.1) and closed loop ones (described in Sect. 2.2.2).

1. Full compensation power control.
   The parameter $\alpha = 1$ compensates all the pathloss
2. Fractional pathloss compensation.
   The parameter $\alpha = \{0.4, 0.5, 0.6, 0.7, 0.8, \text{or } 0.9\}$ and it does not compensate pathloss completely.
3. No power control, and no pathloss compensation.
   Each UE transmit data using its maximum allowed power.
4. Closed loop power control.
   It uses continuously the TPC commands to match each UE received SINR at the eNB side with a predefined target SINR.

2.2.1 Open loop power control strategies

In order to understand performance of the first three strategies it is needed to understand how PSD_{Tx}, and P_0 are calculated.

According to [15], P_0 is calculated using the equation

$$P_0 = \alpha(SINR_t + IN) + (1-\alpha)(P_{max} - 10\log_{10}(M)) \qquad (2.6)$$

where IN is the average noise plus interference level per RB [dBm] and $SINR_t$ is the target SINR. Instead of using (2.6), the interference term will be omitted and a margin within the target SNR will be used to compensate interference, w.r.t. thermal noise. The new equation will be [14, 15]

$$P_0 = \alpha(SNR_t + P_n) + (1-\alpha)(P_{max} - 10\log_{10}(M)) \qquad (2.7)$$

where P_n is the noise power per RB.

Using (2.7) now we can rewrite (2.4) as

$$PSD_{Tx} = \alpha(SNR_t + P_n + PL - P_{max}) + P_{max}. \qquad (2.8)$$

The difference between the first three strategies and how they respond to the change in the power control parameters can be understood from studying PSD_{Tx}, and P_0 through (2.4) and (2.8). We can observe the following.

1. From (2.4), using α = 1, strategy (1) leads to using the same power for all UEs regardless of their distances. By decreasing α, moving from strategy (1) to (2) and (3), each UE will have a different PSD_{Tx} depending on its distance. This can be interpreted as an increase of the variance, or differentiation, between the UEs transmitted power and performance.

2. From (2.8), since usually P_{max} = 24dBm [15], P_n is typically a negative number (a common number might be -116 dBm for a given noise figure and thermal noise power), the result of $(SNR_t + P_n + PL - P_{max})$ is typically negative. Therefore, setting α = 1 results in the lowest transmitted power, and this choice corresponds to strategy (1) with full compensation power control. The lower α, the more the power, as in strategy (2), i.e. fractional pathloss compensation power control. When (α) = 0 is used the UE is transmitting with full power, from equation (2.8) $PSD_{Tx} = P_{max}$, strategy (3): no power control.

From these two points, it should be taken in mind that, during the choice of the power control plan, α can lead to a change in the total cell transmitted power and also in the PSD_{Tx} between different UEs. In fact the effect of α on PSD can be seen in Fig. 2.2.

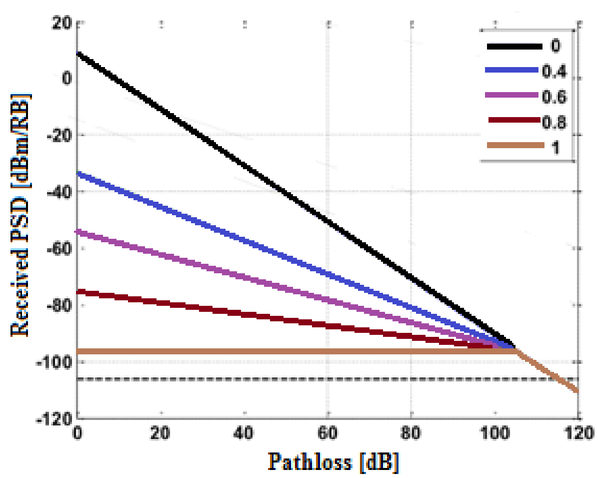


Fig. 2.2 Received PSD for different values of α. If α is not equal 1, the UE power changes with the path loss

2.2.2 Closed loop power control strategy

The strategy (4) in Sect. 2, the closed loop power control, is used to contrast fast channel variations. The UE changes its power setting according to TPC commands from the eNB to the UE. The eNB estimates the SINR of the UE received signal and this SINR estimate is compared with the target SINR. According to the result of the comparison, one of three scenarios occurs affecting the TPC command sent from the eNB to the UE [4, 5, and 23]:

1. If the received SINR is less than the target SINR, the TPC command will order the UE to increase the transmission power.
2. If the received SINR is greater than the target SINR, the TPC command will order the UE to decrease the transmission power.
3. If the received SINR is equal to the target SINR, the TPC command will order the UE to keep the transmission power unchanged.

The TPC commands are sent to the UE over PDCCH. Unless configured otherwise, the UE checks for the TPC commands every subframe. Further information regarding the Δ_{TPC} will be presented in the coming chapter.

Chapter 3

Power control performance

In this chapter a comprehensive study of power control techniques performance is going to be presented with extensive simulation results and graphs.

This chapter will help the reader to be familiar with the different power control techniques, and understand the different power control techniques' performance under different circumstances.

3.1 System model

Power control been tested under the conditions and scenarios listed in Table 3.1. The target is to test the power control techniques for small sites that comprise 7 cells. All the sites have the same assumptions and performance targets, i.e. same rate and SINR. Hence, the power control parameters are the same for all cells.

Traffic models	
User distribution	Uniform
Data generation	full buffer traffic model
Radio network	
Distance attenuation	(44.9-6.5*log(32))*log(d)+34.46+5.83*log(32)+23*log(f/5) d:distance in [m], f:frequency in [GHz]
Shadowing	Standard deviation σ=8 dB
Cell layout	Seven hexagonal cells
Channel model	WIM (WINNER phase 2 model), Urban macro
Cell radius	167, 250m (Inter base station distance 500m)
System model	
Spectrum allocation	10 MHz (using 50 resource block)
Max UE Transmit power	24 dBm
Mean Min Power	-40 dBm
Scheduling	Round robin (RR)
eNodeB receiver	Single antenna

Table 3.1 System model.

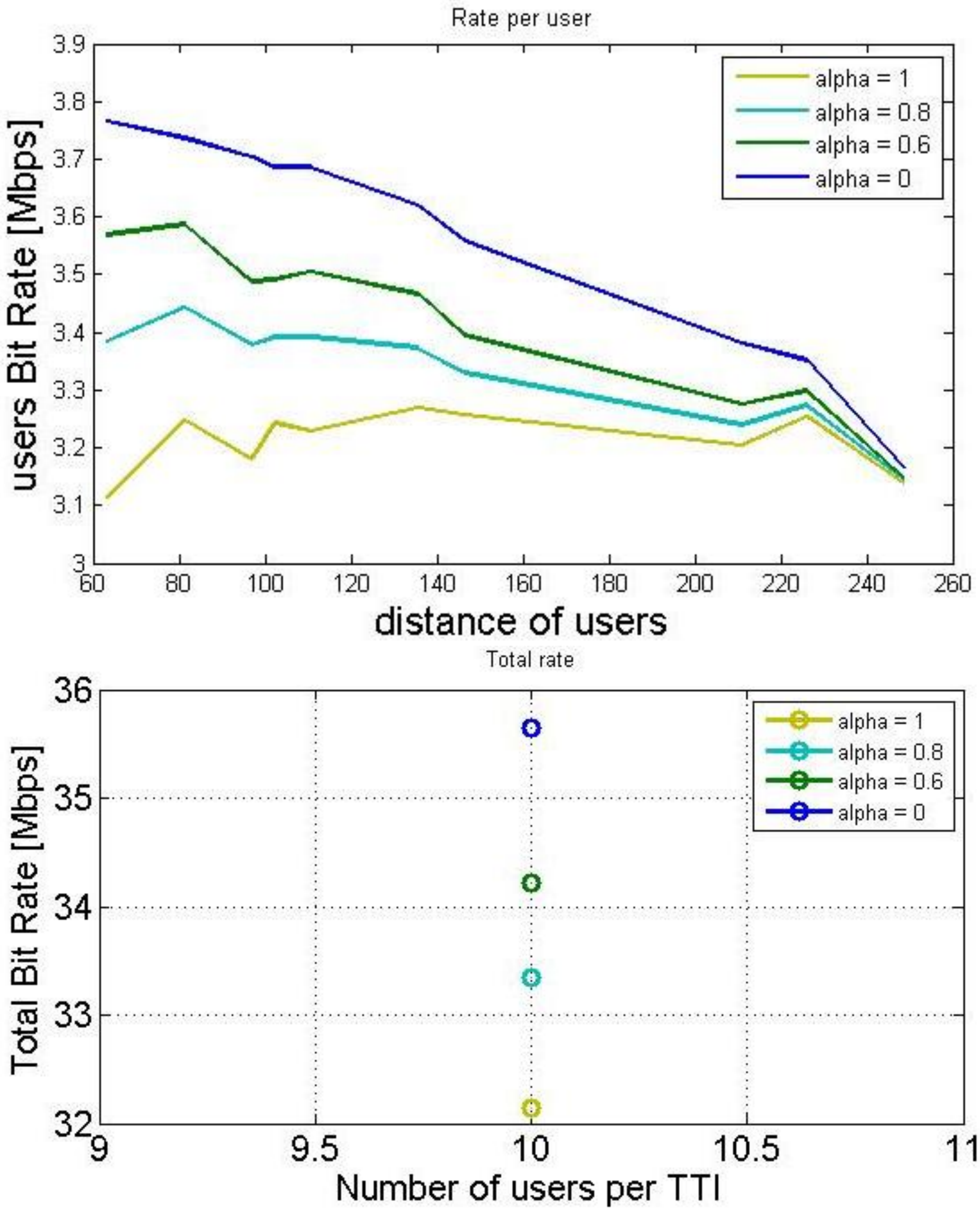


Fig. 3.1 Achieved bit rate per user and total achieved rate for different values of α.

3.2 Evaluation of open loop strategies

The simulation was carried out, as written in Table 3.1, in the WIM channel. All the power control techniques, starting from the OLPC are going to be simulated and studied.

The parameter $\boldsymbol{\alpha}$ and P_0, as calculated from (2.6), are going to be tested in our system, and the results are illustrated in Fig. 3.1. The first thing to be discussed is the effect of α. It was noticed that, as already mentioned in the previous chapter, changing α results in a variance increase: as α decreases (the pathloss is not fully compensated) a difference between users received PSD can be noticed. And, as a result of this change of power, the total achieved cell rate is also affected. When compensating all the pathloss, i.e. α=1, almost a constant SINR and bit rate is achieved for all users. As α is decreased, a higher bit rate is achieved but there will appear a higher variance between users, and the users transmission power changes with distance. Beyond a certain distance, the calculated power, according to the fraction of the pathloss to be compensated, will not be possible to get transmitted; of course when the maximum UE power is reached, even pathloss with α = 1 would not be compensated anymore.

First the simulation was done under non-interference conditions. The next step is to observe the difference after introducing interference into our system.

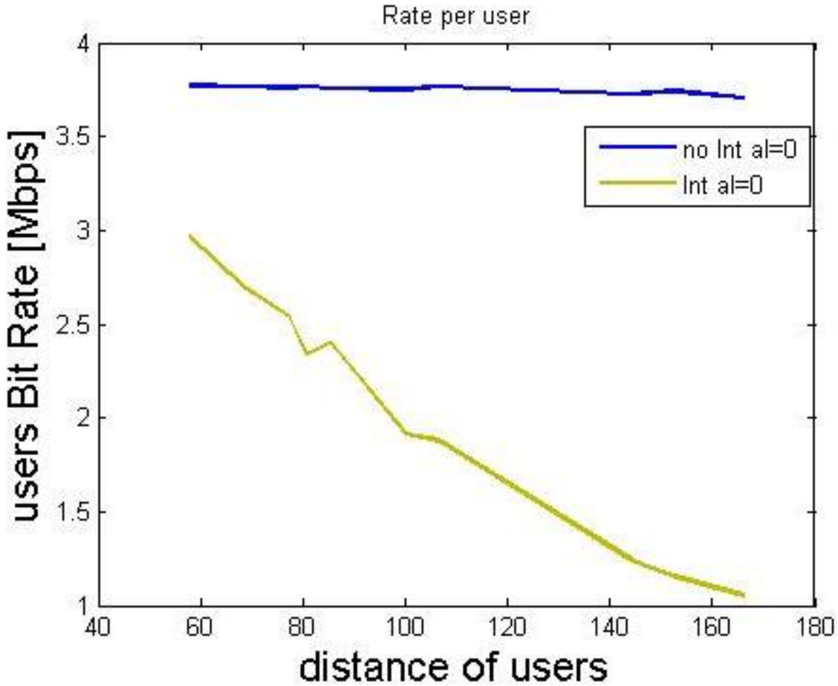
Of course the interference affects and generally reduces the achieved rate. In fact it is observed that the cell experiences a fall of, almost half of its achievable rate. It is also worth noting that users at the edge of the cell experience the biggest decrease in their rate, which means that they are the most affected group by the interference as expected.

3.2.1 Scheduling strategies

It is not so hard to imagine that the scheduling strategy affects the achieved rate. It can be seen from Table 3.1 that RR scheduler is used. In most of the studied cases each user takes more than 1 RB per TTI. Each of these RBs, probably, has different CQI than the others. The question is: How will the scheduler assign the MCSs for the RBs? In this study, two scheduling strategies have been studied: the flexible scheduling and the minimum CQI. Both strategies are going to be explained along with their impact on performance.

Fig. 3.2 illustrates the interference effect in case of using flexible scheduling. Flexible scheduler assigns the best MCS for each RB. Even if the RBs belong to the same user, they can take different MCS. In Fig. 3.3 the minimum CQI (MCQI) scheduler is used. In MCQI, if some RBs belong to the same user, all of them take the same MCS, which is, in this case, the MCS belonging to the RB with the lowest CQI. Using MCQI leads to a further decrease in the achievable rate, since the worst RB for each user is used. The MCQI will be used through the rest of this study.

Even though the MCQI attains a reduction in the performance, this study assumes the worst case scenario in all the situations.



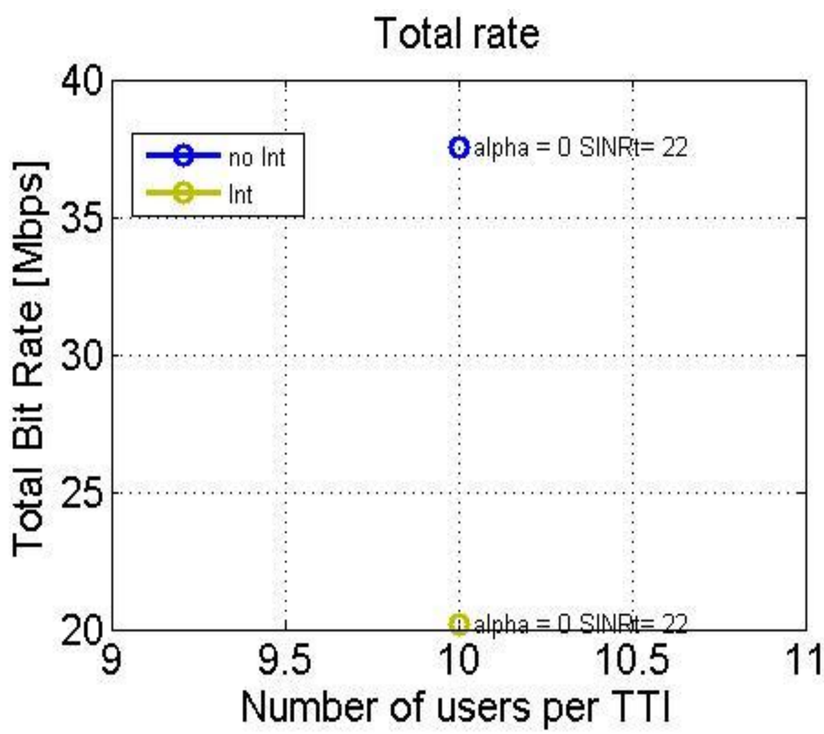


Fig. 3.2 Achieved bit rate per user and total achieved rate using the flexible scheduler. Interference case vs. non-interference case

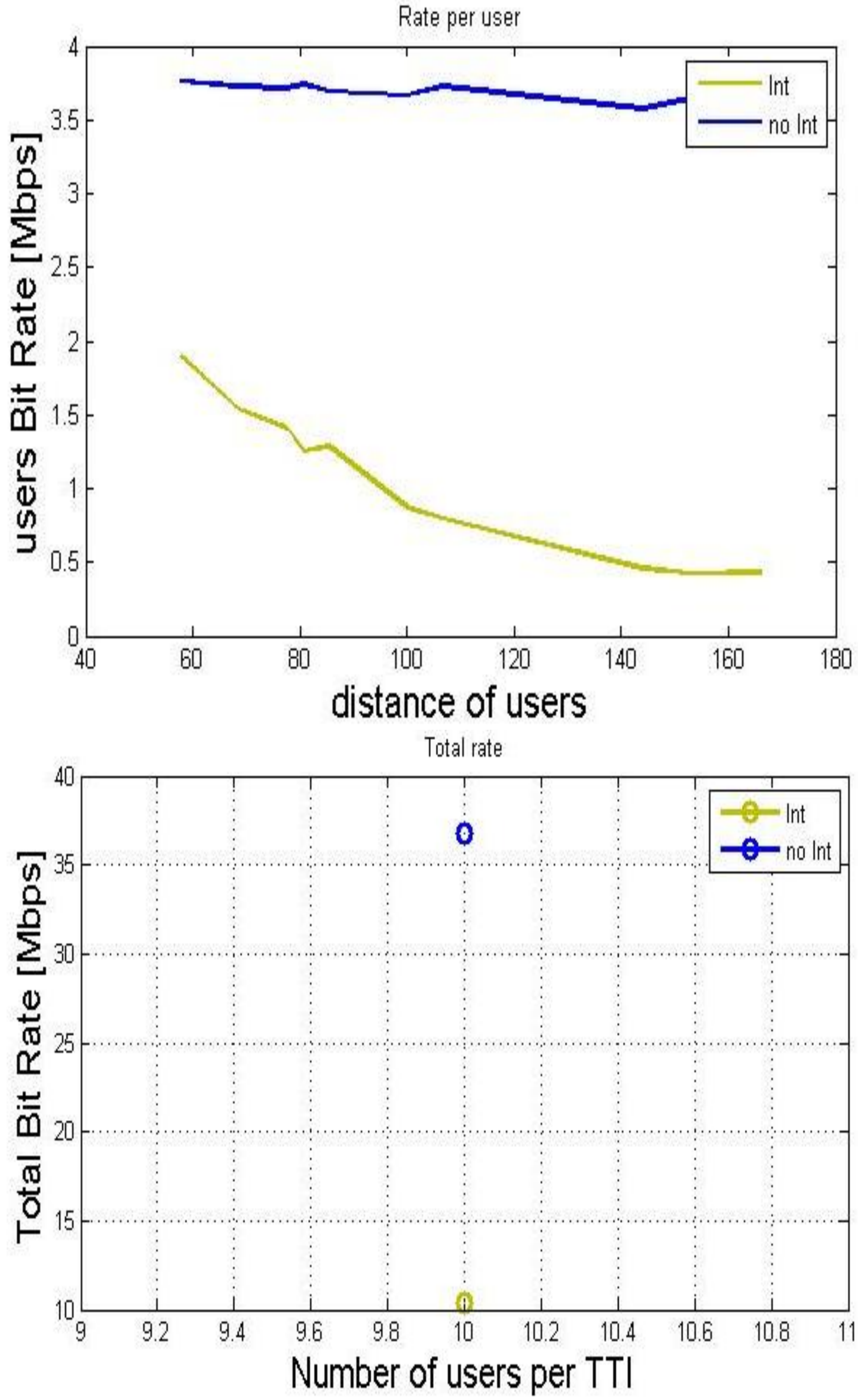


Fig. 3.3 Achieved bit rate per user and total achieved rate using MCQI. Interference case vs. non-interference case

3.2.2 Fractional power control

The next step is to study the effect of the fractional power control (FPC) under interference conditions. Using power control mainly means focusing on the two parameters α and $SINR_{target}$, in (2.4), 2.6) or (2.8). $SINR_{target}$ indicates the value of the SINR to be achieved without taking pathloss into account. In general, not necessarily true in all situations, the higher the desired SINR, the higher the $SINR_{target}$ and the higher the transmitted power. In other words, if there is a need to achieve a high SINR, the transmitted power is increased. As already mentioned, α is the amount of pathloss to be compensated. The question is: if the pathloss has been fully compensated, can any given $SINR_{target}$ be achieved ? The answer is clearly negative for two reasons: the former is that UEs have a fixed maximum power and users with high pathloss will spend most of their power in compensating that path-loss and they might not have enough power to achieve the desired rate. The latter is that increasing the power, in order to have higher SINR, will lead to an increase of the inter cell interference.

The parameter α equal to zero means, according to (2.8), that the UE max power is used. In this situation it can be said that:

- From (2.8), Changing $SINR_{target}$ has no effect on the equation or the result, since the $SINR_{target}$ term vanishes from the equation.
- Using maximum power means that all the UEs are targeting the highest rate,
- The maximum interference condition is achieved.

Using the maximum power will lead to achieving a high average cell rate but, on the other side, it will lead to a very low final rate for users with a high pathloss, on the edge of the cell, due to the high interference.

On the other side, parameter α equal to 1 means that pathloss should be fully compensated, as can be seen by (2.4):

$$\text{PSD}_{\text{Tx}} = P_0 + PL_{DL} \quad (3.1)$$

$$\text{PSD}_{\text{Rx}} = \text{PSD}_{\text{Tx}} - PL \quad (3.2)$$

$$\text{PSD}_{\text{Rx}} = P_0 + PL - PL \quad (3.3)$$

$$\text{PSD}_{\text{Rx}} = P_0 \quad (3.4)$$

As already mentioned, α affects the amount of power to be transmitted and the variance of the received power among different users. Using α = 1, under certain conditions, cancels any variance among users, since we are canceling the whole pathloss in each link budget.

By using α lower than 1, an intermediate state between the previous two cases is attained: pathloss is partially compensated and a certain amount of variance is observed as the value of α is decreased.

In Fig. 3.4 - 3.5 it is illustrated the difference in performance between the three types of configurations, α = [0, 1, < 1]. This difference between the three FPC types changes the selected $\text{SINR}_{\text{target}}$ accordingly. First of all, α = 0 is equivalent to sending with maximum transmission power, and it is independent of $\text{SINR}_{\text{target}}$. The maximum transmission power causes maximum interference and the most affected users are those at the cell edge (CE). On the other hand, in case of values of α different from 0, $\text{SINR}_{\text{target}}$ has a relevant impact on the obtained results.

Choosing low $\text{SINR}_{\text{target}}$ allows the pathloss to be compensated without causing too much interference (especially to CE users).

In general, at a (medium - low) $SINR_{target}$, the higher α (going from 0 to 1), the better CE users' performance, and the worse the cell center performance w.r.t. low α, as already observed in Fig. 2.2. Since $SINR_{target}$ is not too high, all the users can achieve this $SINR_{target}$ without exceeding the allowed UE P_{max} and a uniform rate for all the users is achieved. Also, the interference turns out to be not too high, since the used power is not so high.

As it can be seen from Fig. 3.4, $\alpha = 0$ achieves the maximum cell rate but the lowest CE users performance. On the other hand, $\alpha = 1$ is the best for CE users but it achieves the lowest cell rate, and also the lowest performance for users close to the eNB - cell center (CC) users - in comparison with other α values. Choosing FPC ($\alpha < 1$) attains an intermediate performance in all the aspects.

On the other side, a high $SINR_{target}$ gives a different behavior, as it can be seen from Fig. 3.5:

1. As already mentioned, $\alpha = 0$ is independent of $SINR_{target}$, thus the behavior/performance of the $\alpha = 0$ case is not affected by the change in the value of $SINR_{target}$.
2. At $\alpha = 1$ and $\alpha < 1$, increasing $SINR_{target}$ in these two cases leads to increase in the transmission power. Users in this case transmit with power almost equal, or slightly less than the maximum allowed transmission power, i.e. $\alpha = 0$ case. Furthermore, the achieved "rate per user" is quite similar to the case $\alpha = 0$, and a small increase in the cell's average rate over the case $\alpha = 0$ is observed.

It will be illustrated later that the maximum average achievable rate for the cell is usually attained at a transmission power slightly less than P_{max}.

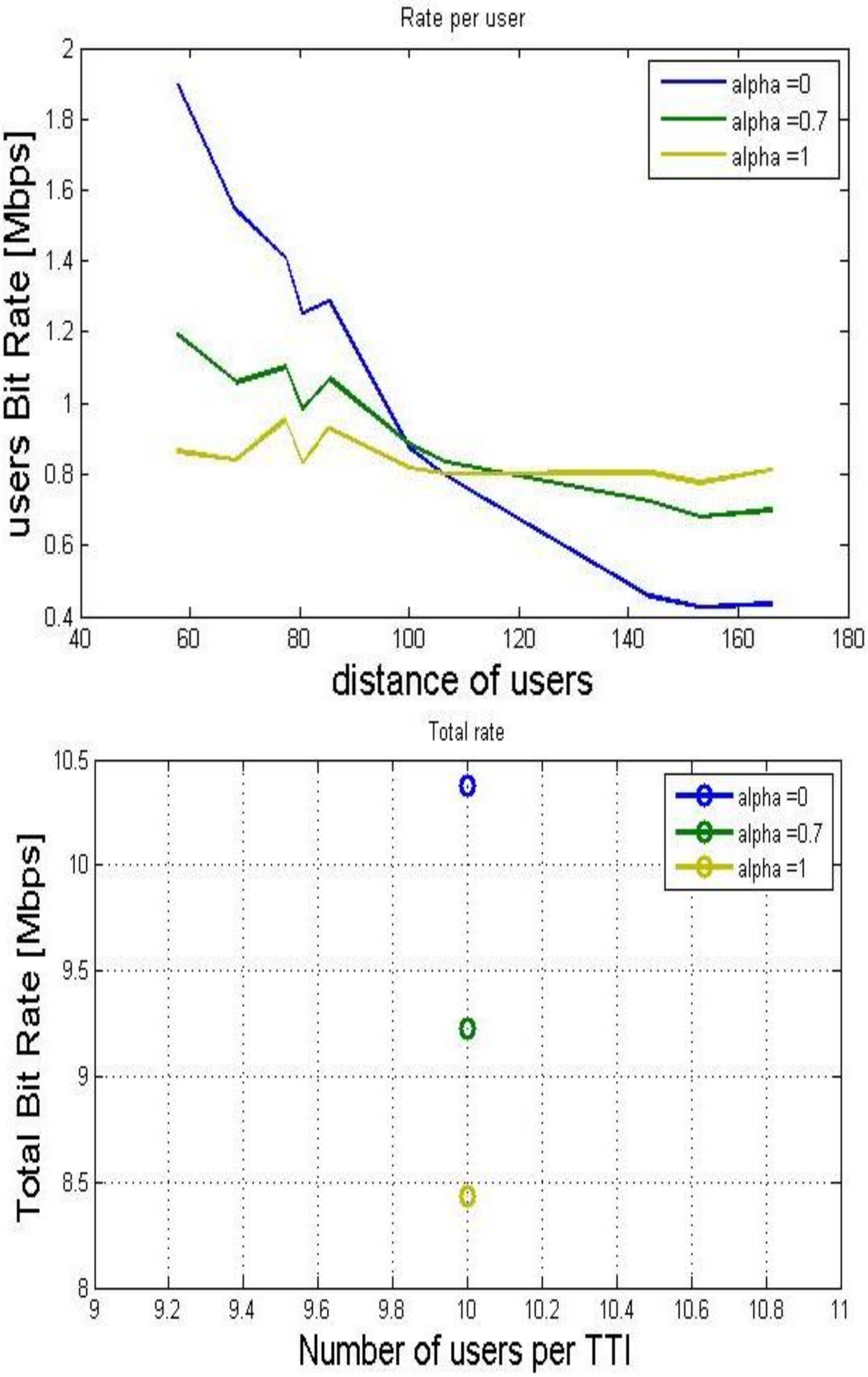


Fig. 3.4 Achieved bit rate per user and total achieved rate for different values of α using low-medium SINR target.

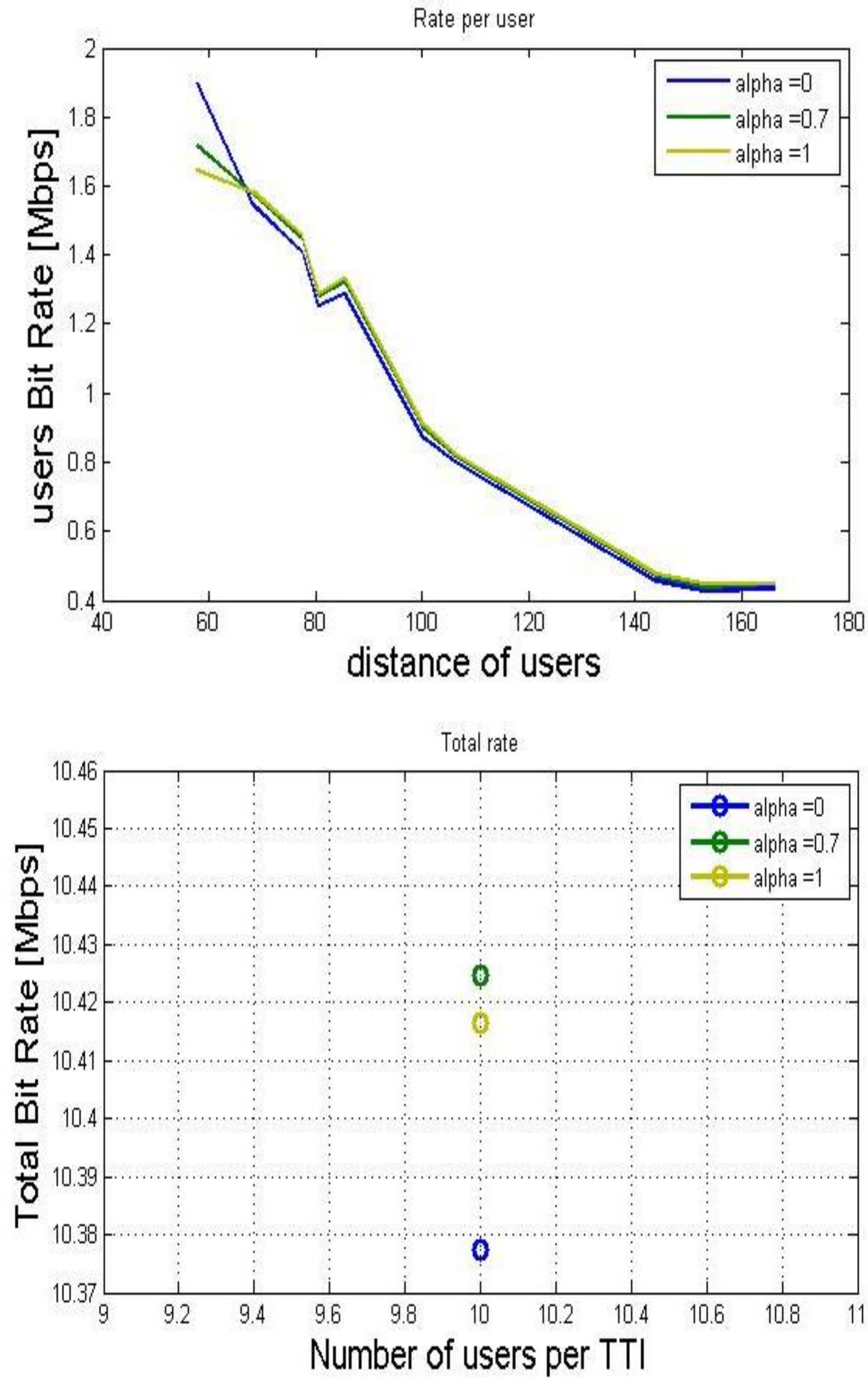


Fig. 3.5 Achieved bit rate per user and total achieved rate for different values of α using high SINRtarget.

3.3 Evaluation of closed loop strategy

Closed Loop Power Control (CLPC) starts and operates, around the values reached by OLPC. CLPC tries to adjust the received SINR in order to reach a desired SINR in a precise way. The eNB sends a feedback command instructing the UE to decrease, increase, or keep its transmission power.

Choosing a reasonable, small-medium, $SINR_{target}$ allows all the users to achieve it. It can be seen in Fig. 3.6 that, more or less, all the users can achieve the same desired $SINR_{target}$, which is equal to the average achieved $SINR_{target}$.

When the $SINR_{target}$ is increased, not all the users, especially the CE ones, can achieve the desired $SINR_{target}$ and the variance of the received PSD as well as the achieved rate of the users start to increase. The more the $SINR_{target}$ is increased, the more the CLPC tries to increase the transmitted power and, due to pathloss, interference, and maximum transmitted power constraints, the users start to reach their maximum transmitted power one by one. This typically ends when all users reach their maximum transmission power, without being able to achieve the desired $SINR_{target}$, similarly to the OLPC case with α =0, as shown in Fig. 3.7.

As already mentioned in the previous chapter, before deciding the TPC command, the received SINR must be compared with the $SINR_{target}$. However, the estimated received SINR ($SINR_R$) is smoothened by means of an exponential filter: a memory parameter μ is used and, the smaller μ, the longer the "memory" of the exponential filter and the greater the smoothing degree of the estimated received SINR. The parameter μ is tested here for values {0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1}. All the simulations have been tested with these values , but for the sake of simplicity, only one value is plotted in some figures, usually the maximum μ = 1 or the minimum μ = 0.1. The smoothing filter is

$$SINR(t) = (1 - \mu)\ SINR(t - 1) + \mu SINR_R(t) \qquad (3.5)$$

and, based on the difference between $SINR_{target}$ and SINR(t) the value of the TPC command to be transmitted is decided. The possible values transmitted by the TPC command are $\Delta = [-1, 0, 1, \text{and } 3]$. The closed loop correction value is obtained from the SINR difference as in the following list:

- If difference [dB] <= −1 then −1 is sent,
- Else if −1 < difference [dB] <= 1 then 0 is sent,
- Else if 1 < difference [dB] <= 5 then 1 is sent,
- Else if difference [dB] > 5 then 3 is sent.

It has to be noted that the implementations and algorithm of the CLPC is vendor specific.

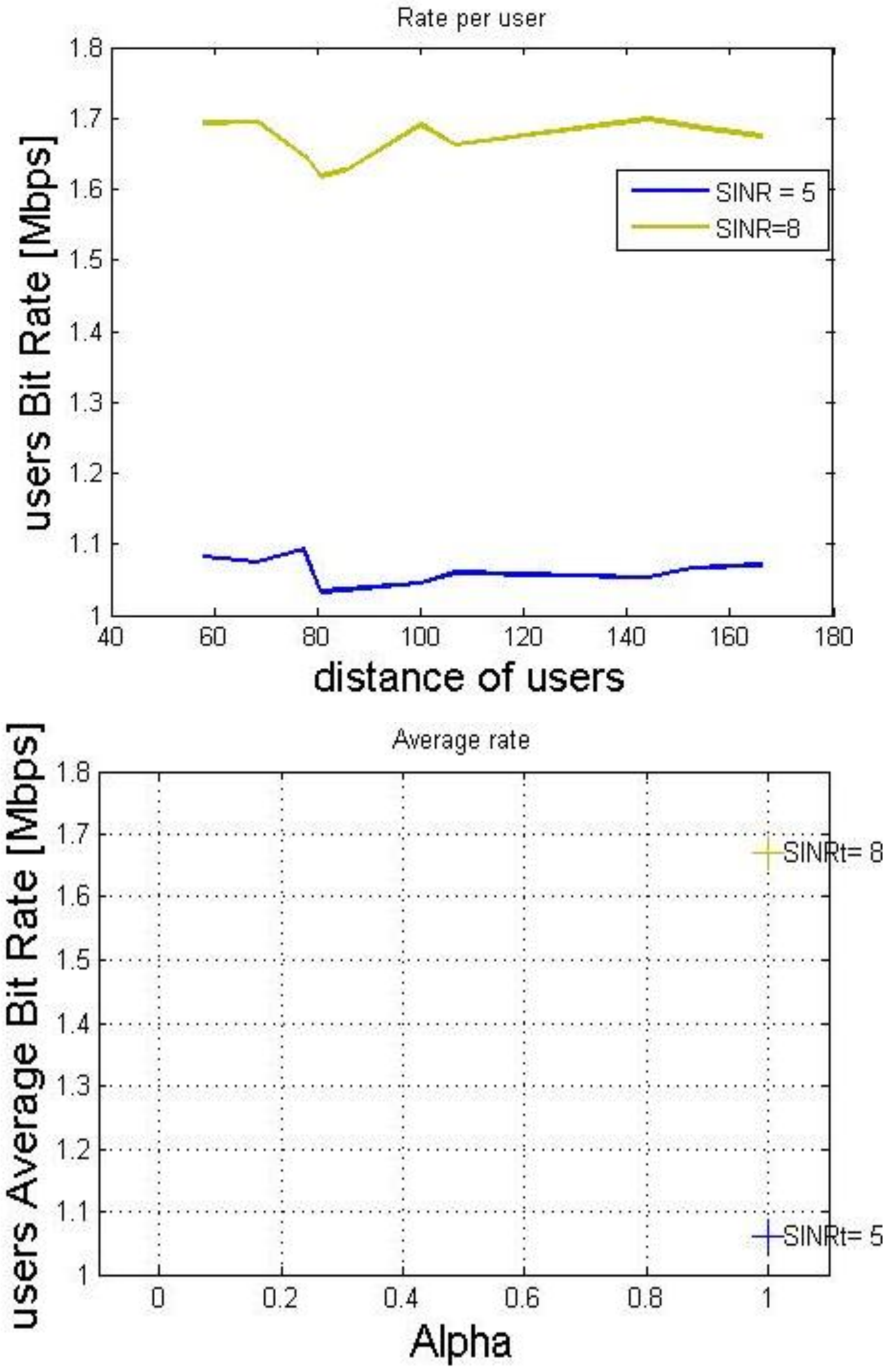


Fig. 3.6 Low-medium SINR for CLPC can be achieved by all users.

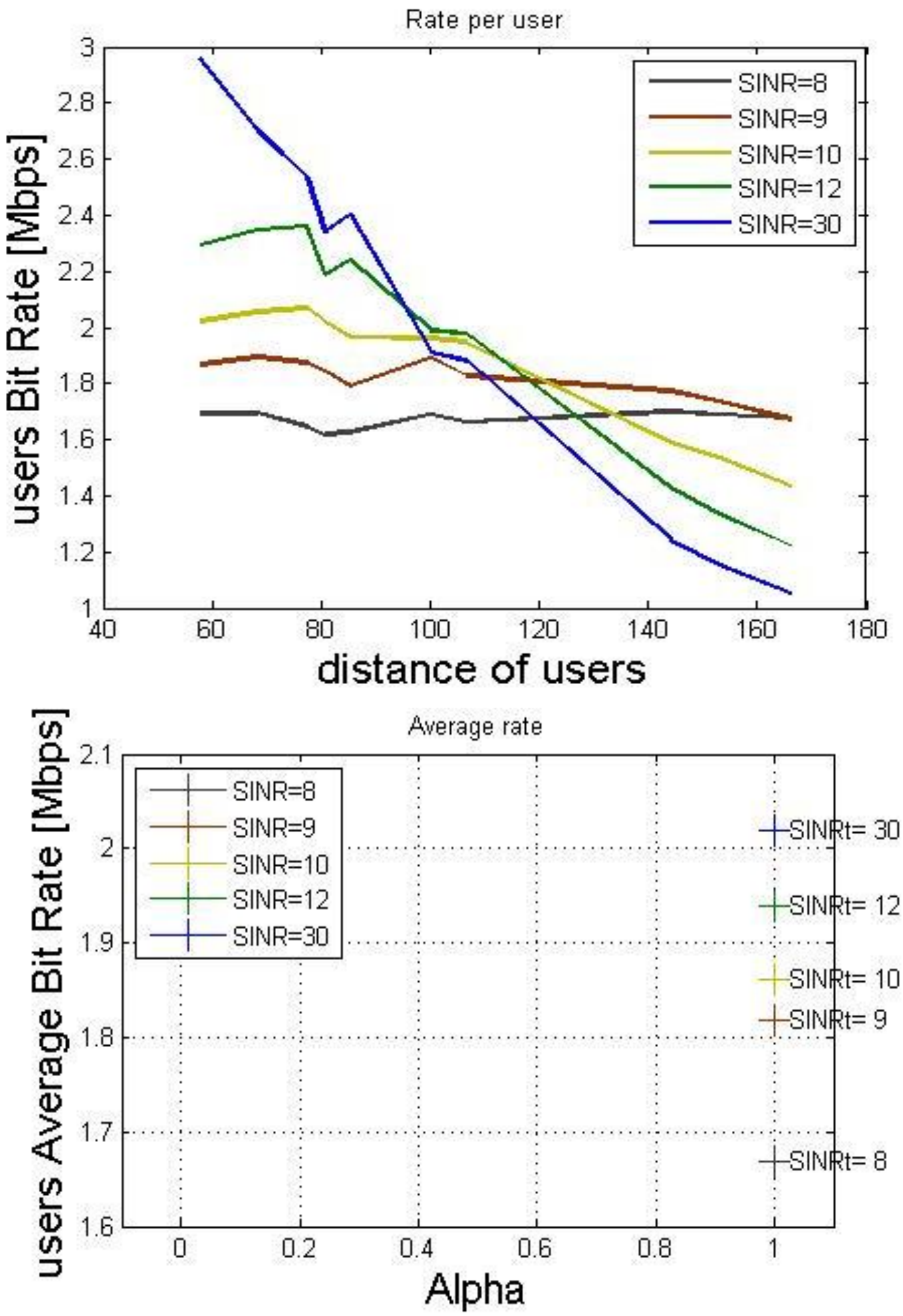


Fig. 3.7 As SINR increases users' rate start to lose uniformity.

3.4 The traffic impact

One of the goals of this study is to evaluate performance of power control at different interference or traffic levels. In this thesis, the traffic is changed by means of changing the number of users, keeping the number of already assigned RBs, to each user, fixed.

Decreasing the number of users and keeping the number of assigned RBs fixed causes a decrease in the interference, since the number of interfering users on each RB is decreased. The reduction in the interference leads to an increase of the achieved SINR per user and an increase in the achieved rate per user.

Decreasing the traffic in case of non-interference scenario has no effect on the achieved rate, since the interference is not taken into account. It is also worth noting that using a small $SINR_{target}$ reduces the interference, since a lower transmission power is used, and, as a result, the difference between the interference and non-interference cases is reduced. The effect of traffic is illustrated Fig. 3.8. In case of CLPC the same effect of the traffic is observed, as illustrated in Fig. 3.9.

Also, it has to be noted that, in the case of very low traffic (e.g. 20%), the probability of having interference is small, since the number of users and, more importantly, the number of used RBs is very small. However, there is a big difference in the performance between the interference and non-interference cases. This is because the MCQI scheduler is used: if only one RB, of any of the user RBs, is subject to interference, the used MCS and the rate achieved by this user will be low even if its other RBs are not affected by any interference, since the MCS is selected according to the worst RB state.

On the other hand, as already mentioned, increasing the traffic in the system leads to an additional decrease of the achieved rate, as the number of interferes per RB increases, i.e. with more degradation in the performance of this RB and of its user. Furthermore, when the number of users and the number of used RBs in the system is high, the probability of having two or more interfering RBs is high as well and this will lead to a reduction in the performance of most of the users.

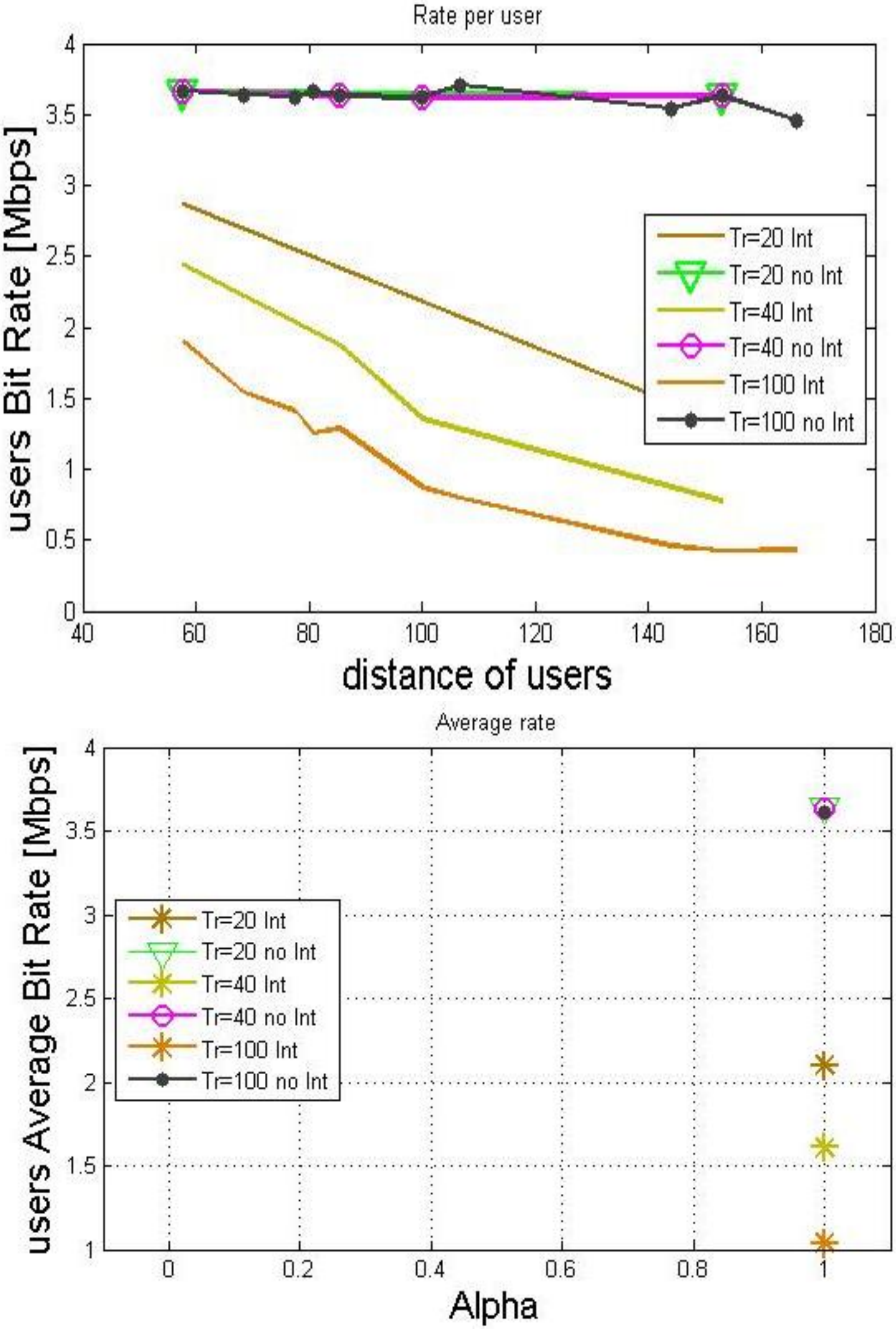


Fig. 3.8 Effect of changing traffic (interference, and non-interference cases) on OLPC systems.

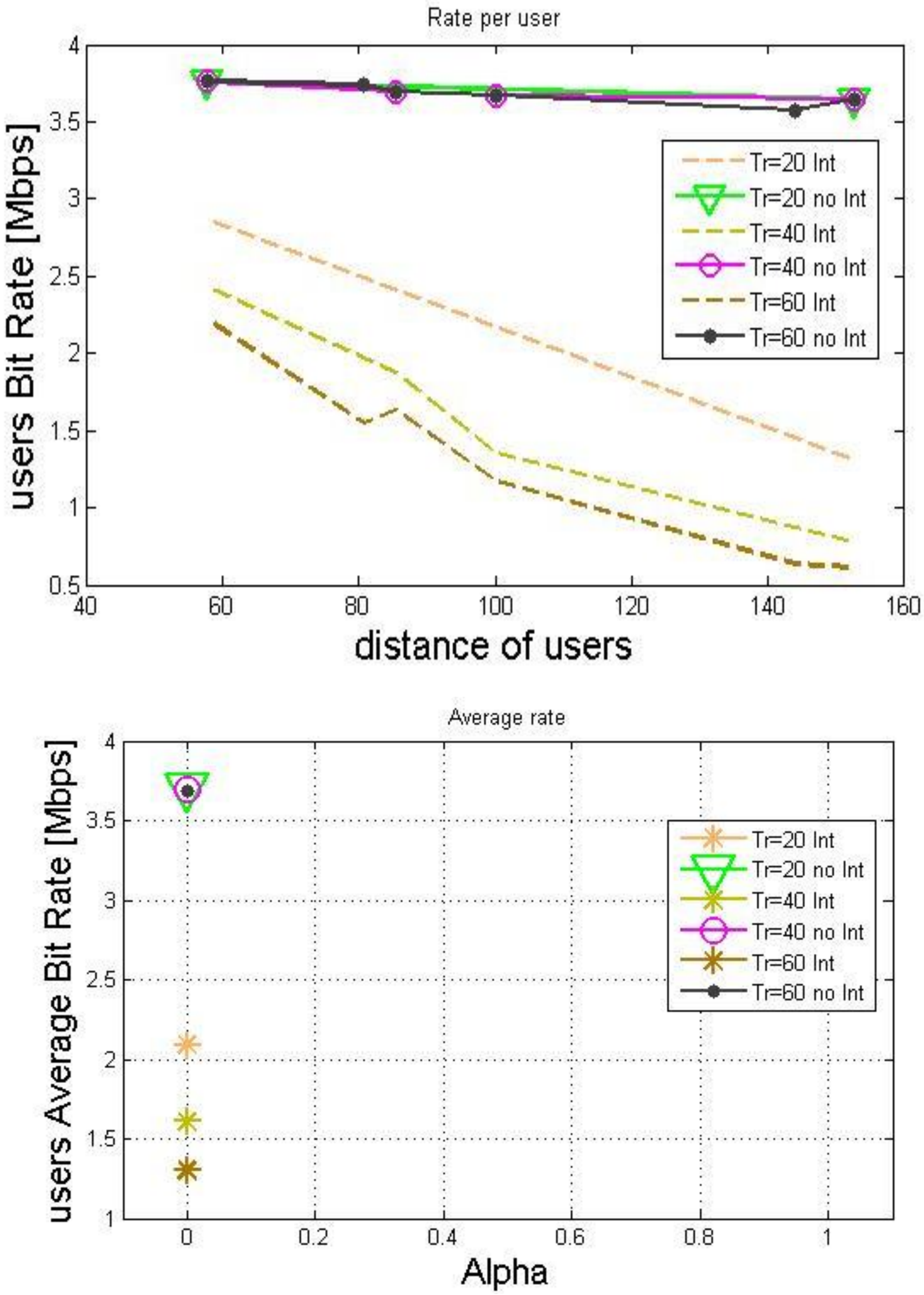


Fig. 3.9 Effect of changing traffic (interference, and non-interference cases) on CLPC systems.

3.5 The pathloss role

According to users' pathloss, the most suitable power control technique is different. For example, users closer to the eNB achieve their best performance under OLPC, while users at cell edge need CLPC to adjust their power and to overcome their bad conditions.

In Table 3.2, the users are listed according to the pathloss ascending order. The rate achieved by each user is recorded as well as the power control technique and the necessary parameters to achieve that rate. It is worth noting that, in general, it is harder for CE users than CC users to achieve a given target rate, due to pathloss and interference conditions. In the following, the behavior seen in the table is going to be explained.

CLPC tries to achieve an equal target performance for all users. Thus the algorithm will attempt to increase the performance of the CE users and this will affect, negatively, the performance of other users, because increasing cell edge users power and trying to force them to achieve high rate, will lead to an increase in the interference. It is also noticed that CLPC is better for the last group of users, i.e. users closer to the cell edge. On the other hand, using OLPC and targeting high bit rate will cause the users at the edge to achieve low rate, because of their position and vulnerability to interference. Furthermore, without any effort to increase their performance, the CE users will maintain a low rate, and consequently the users closer to the center will have good performance since they will be affected by less competitors and weaker inference sources. Finally, it can be noticed that the first users in the table (cell center) take more benefit from selecting OLPC for the whole system.

User	Max Rate	Closed/ Open	Alpha	SINR	Used RBs percentage
1	2.9748	Open	1	38	100
2	2.7301	Open	1	36	100
3	2.6065	Closed	0.6	16	100
4	2.4059	Open	1	34	100
5	2.5124	Open	1	32	100
6	2.1880	Closed	0.5	10	100
7	2.1541	Closed	0.8	12	100
8	2.0625	Closed	0	10	100
9	2.0855	Closed	0.6	10	100
10	2.0705	Closed	0.7	10	100

Table 3.2 Most suitable technique for each user using flexible scheduling.

As already discussed in Sect. 3.5.2, changing the scheduling strategy affects the achieved rate. Here it can be noticed that not only the rate is affected, but also the most suitable power control strategy technique for each user. Results from Table 3.2 were obtained using flexible scheduling, and results from Table 3.3 were obtained using MCQI.

In Table 3.3, it can be noticed that now CLPC is the best for all the users, including users closer to the eNB. This happens because OLPC sets the power setting for all the RBs of the users without doing any further adjustments, and it is most likely to happen that one RB will have bad channel conditions, due to fast fading or interference, since the MCSis decided according to the worst RB. On the other hand, CLPC is originally implemented as a countermeasure against fast fading and CLPC tries constantly to adjust and improve the performance of all the RBs, improving the final performance of each user.

User	Max Rate	Closed/ Open	Alpha	SINR	Used RBs percentage
1	1.9136	Closed	0	30	100
2	1.6134	Closed	0	26	100
3	1.5050	Closed	0.5	24	100
4	1.4484	Closed	0	22	100
5	1.4416	Closed	0	22	100
6	1.1718	Closed	0.6	20	100
7	1.1086	Closed	0.4	20	100
8	1.1122	Closed	0.5	12	100
9	1.0253	Closed	0	16	100
10	1.0934	Closed	0.8	14	100

Table 3.3 Most suitable technique for each user using MCQI scheduling.

3.6 Optimal parameters for maximum average rate

An extensive simulation campaign was performed with all the possible combinations of the power control parameters. The simulations were done for both OLPC and CLPC at different levels of traffic. The parameters that achieve the maximum average rate are reported in Table 3.4.

In Table 3.4, the maximum average rate is reported along with the transmission power needed to achieve it. It can be observed that:

1. The difference between performance of OLPC and CLPC is not so big;
2. As the traffic percentage - the traffic is defined in Sect. 3.4 - increases, the maximum achievable rate is decreased.

It is worth noting that in CLPC the SINR is the actual desired SINR that the system aims to achieve. On the other hand, in OLPC the value for SNR_{target} is chosen with a margin for the interference that must be taken into account, because the OLPC parameters are adjusted only once at the beginning of the transmission.

3.6.1 Impact of the cell radius

In Table 3.5, the cell radius was reduced from 250 m to 167 m, keeping the inter-base station distance unchanged. It can be seen, from the results, that the maximum average achievable rate is higher than that of 250 m. This is intuitive, because the average pathloss turn out to be smaller and the average pathloss of interfering users is higher.

Max Avg. Rate	P_{Tx} [dBm]	Closed/ Open	Alpha	SINR	μ	Traffic percentage
2.7696	17.0103	Op	0	6	-	20
2.7696	17.0103	Cl	0	44	0.1	20
1.3592	17.0103	Op	0.9	34	-	40
1.3572	16.9979	Cl	0	12	0.1	40
1.0518	16.9396	Op	1	32	-	60
1.0714	16.8009	Cl	0.7	8	0.1	60
0.9191	16.9870	Op	0.7	36	-	80
0.9305	16.8003	Cl	0.4	8	0.1	80
0.7476	16.9839	Op	1	36	-	100
0.7490	16.8785	Cl	0	8	0.1	100

Table 3.4 Highest average rate achievable by OLPC, and CLPC at different values of traffic

Max Avg. Rate	P_{Tx} [dBm]	Closed/ Open	Alpha	SINR	μ	Traffic percentage
2.9615	17.0103	Op	0	6	-	20
2.9615	17.0103	Cl	0	46	0.1	20
1.8900	17.0103	Op	1	36	-	40
1.8904	16.9905	Cl	0.4	18	0.1	40
1.5002	16.8463	Op	0	34	-	60
1.5161	16.6994	Cl	0.9	12	0.1	60
1.2757	17.0103	Op	0	38	-	80
1.3119	16.6981	Cl	0.4	10	0.1	80
1.0712	17.0103	Op	0	38	-	100
1.0992	16.5757	Cl	0.4	8	0.1	100

Table 3.5 Highest achievable average rate by OLPC, and CLPC at different values of traffic after reducing the cell radius to 167m.

3.6.2 Impact of the number of users per cell

Changing the number of users in the cell changes the number of available RBs/user, the transmitted power per RB, the induced interference and the achieved rate per user.

A comparison is reported in Tables 3.6 - 3.7; the number of users per cell was changed from 10 users per cell to 16, for both cell radius (250 m and 167 m). The total achieved rate for all users, the average achieved rate per user, the average transmitted power per RB and the average received interference per RB were stored and compared.

It has to be noted that increasing the number of users in the cell will lead to a decrease of the number of available RBs per user and, consequently, to a higher PSD, higher transmitted power per RB and higher interference power per RB in the system.

The above described effects can be observed in Tables 3.6 and 3.7: at any value of traffic, the transmitted power per RB is higher in the scenario of 16 users per cell than that of 10 users per cell. Also, the interference power per RB is higher in this scenario. Since the RBs have more power, they are able to achieve a higher rate, and the total rate of the system is higher. However, since the users now have a fewer number of RBs, the average achieved rate per user is lower even if each RB achieves higher rate.

It is noticed that the highest rate is achieved when using a lower cell radius, equal to 167 m, since it has lower interference than that of 250 m, as already mentioned before, using 16 users per cell.

No. of users	Max Tot. Rate	Max Avg. Rate	P_{Tx} [dBm]	Int. [dBm]	Closed/ Open	Traffic percentage
10	5.5392	2.7696	17.0103	-88.7036	Op	20
16	7.3854	2.4618	18.8509	-86.4378	Op	20
10	5.4368	1.3592	17.0103	-85.8899	Op	40
16	7.7394	1.2899	14.8938	-86.9036	Op	40
10	6.4287	1.0714	16.8009	-84.7328	Cl	60
16	8.1538	0.8154	18.8697	-81.6585	Cl	60
10	7.4442	0.9305	16.8003	-83.0790	Cl	80
16	8.8086	0.6776	18.4875	-81.0003	Cl	80
10	7.4896	0.7490	16.8785	-81.6806	Cl	100
16	8.9238	0.5577	18.7421	-79.4890	Cl	100

Table 3.6 Difference in performance when the system has 10 users per cell and 16 users per cell. Cell radius is 250 m.

No. of users	Max Tot. Rate	Max Avg. Rate	P_{Tx} [dBm]	Int. [dBm]	Closed/ Open	Traffic percentage
10	5.9230	2.9615	17.0103	-89.3249	Op	20
16	7.4913	2.4971	18.8509	-87.4664	Op	20
10	7.5617	1.8904	16.9905	-87.2772	Cl	40
16	9.0701	1.5117	18.6854	-85.2169	Op	40
10	9.0966	1.5161	16.6994	-85.4076	Cl	60
16	11.3680	1.1368	18.3488	-83.0280	Cl	60
10	10.4953	1.3119	16.6981	-84.1248	Cl	80
16	12.5758	0.9674	18.5592	-81.9302	Cl	80
10	10.9921	1.0992	16.5757	-82.8735	Cl	100
16	13.1783	0.8236	18.8405	-80.4954	Cl	100

Table 3.7 Difference in performance when the system has 10 users/cell and 16 users/cell. Cell radius 167m.

3.7 Impact of target SINR

The effect of changing the $SINR_{target}$ on both the transmitted power and the achieved rate for different values of α is investigated in this Section.

In the graphs it is shown that changing the value of α has different effects depending on the value of the SINR, i.e. for high SINR or low SINR.

3.7.1 $SINR_{target}$ vs. transmitted power

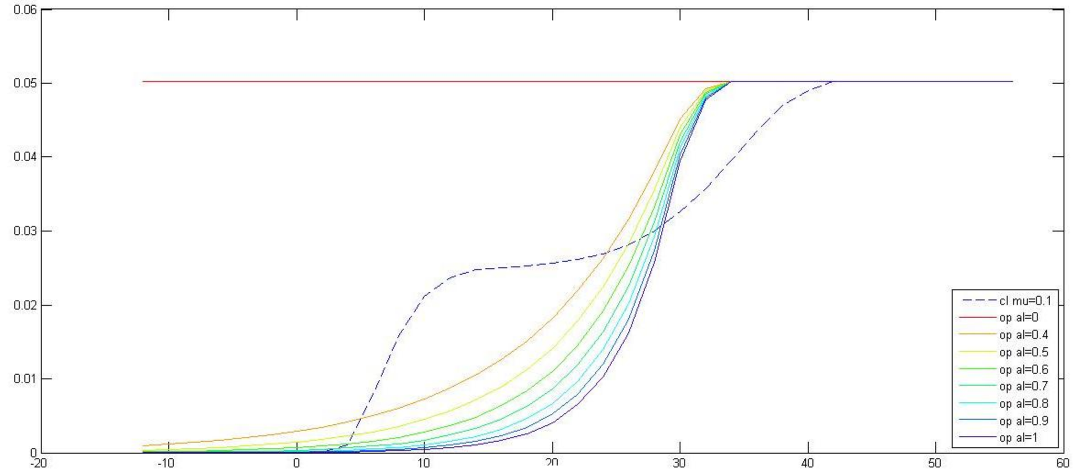
In Fig. 3.10 the average consumed power on the cell was plotted against the used $SINR_{target}$ under different traffic values. Both the behavior of CLPC and OLPC are reported and different values of α were used for the OLPC.

For the OLPC, it is noticed that, as $SINR_{target}$ increases, the average transmitted power increases as well, till the maximum allowed transmit power. This behavior can be understood from (2.4) as the transmitted power is decided according to this equation and it is fixed throughout the transmission process. On the other hand, the behavior of CLPC is slightly different because the amount of power to be transmitted is always varied to respect the $SINR_{target}$ in accordance with the channel and interference status. Yet, as the $SINR_{target}$ increases, the related power in general increases as well.

As already mentioned before, α has two effects: one is that it generates variance among users, the second is that, decreasing α increases the transmitted power, as shown in (2.8) and also clear in Fig. 3.10. It can be seen from Fig. 3.10 that, as the value of $SINR_{target}$ increases, the effect, w.r.t. the transmitted power, of changing α is not so relevant anymore. This can also be understood from (2.8): the effect of changing α on the PSD_{Tx} becomes small and, moreover, at higher $SINR_{target}$ some users reach their maximum transmitted power and, as a consequence, any further attempt to increase the power does not lead to anything.

The other difference between OLPC and CLPC is that, in CLPC, as the traffic, i.e. interference, decreases, the transmitted power needed to achieve the same SINR decreases as well. It can be seen from (3.6) that as interference (Int) decreases, the needed transmitted power (P_{Tx}) will also decrease:

$$SINR = \frac{P_{Tx}G}{N+Int}. \quad (3.6)$$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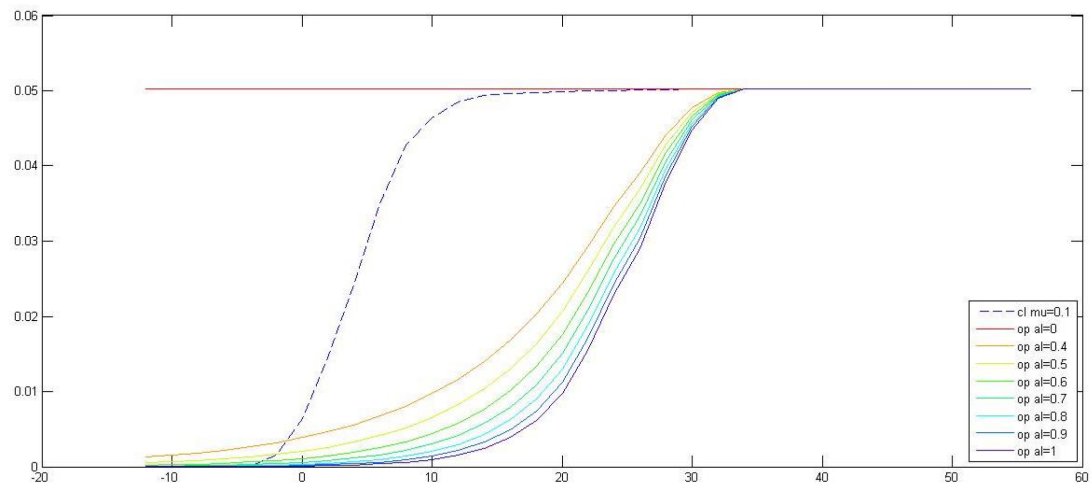
(a)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op al=0
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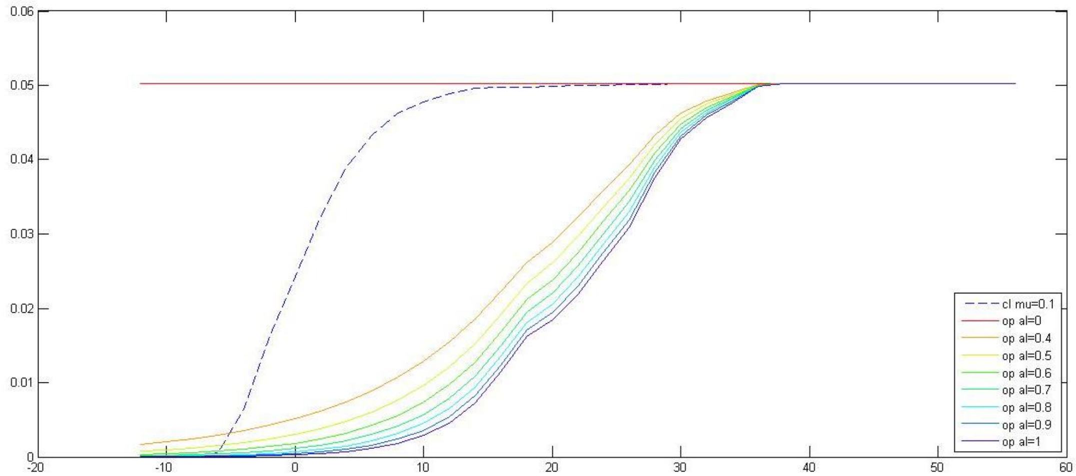
(b)



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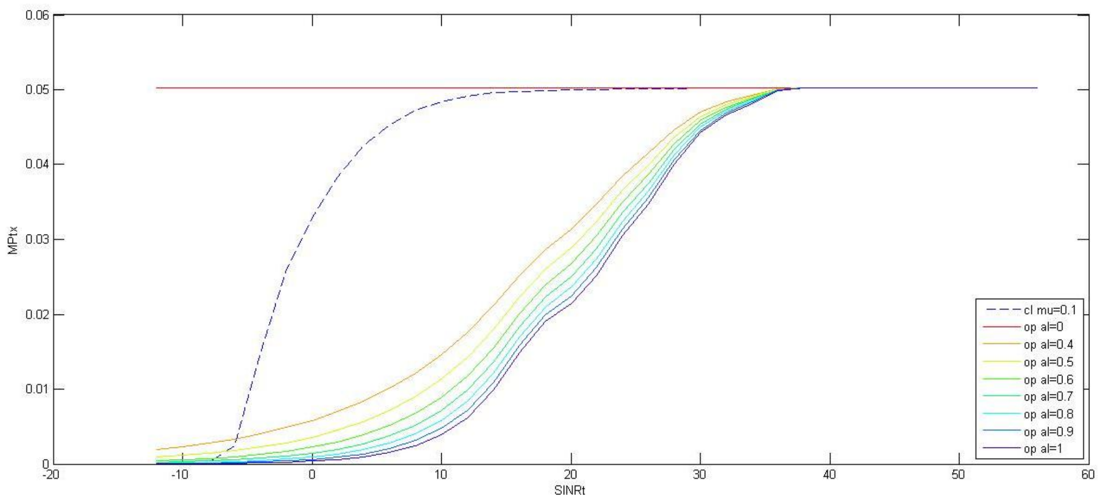


(d)

Fig. 3.10 Effect of $SINR_{target}$ on P_{Tx} at different values of traffic

(a) traffic = 20%, (b) traffic = 40%,(c) traffic = 80%, (d) traffic = 100%

3.7.2 SINRtarget vs. achieved rate

In Fig. 3.11, the average achieved rate of the cell was plotted against the used $SINR_{target}$ under different traffic values. The behavior of both CLPC and OLPC was plotted and different values of α were used for the OLPC.

It has to be noted that, for the tested system, the power control is applied to all the cells equally: $SINR_{target}$, number of available RBs, and α are the same for all the cells. This means, for OLPC, that the increase in average transmitted power is the same for the main user as well as for every other interfering user. Hence, it can be noticed that at higher values of traffic, where the probability of interference is close to 100%, the received SINR will not change even when the transmitted power is changed; this is confirmed until some users reach their maximum transmission power state and then a difference can be noticed in the received SINR and in the achieved rate. This behavior is illustrated in Fig. 3.11 and it can be proven using a simplified mathematical formulation.

A simple representation of the received SINR in dB ("sinr" in the linear representation) will be given , as in (3.7), by

$$\mathrm{sinr} = \frac{\mathrm{p_{tx}/pl_m}}{\mathrm{n+int}} \qquad (3.7)$$

Since the receiver thermal noise is not affected by the amount of the transmitted power, it will be omitted for simplification, and we consider

$$\mathrm{sinr} = \frac{\mathrm{p_{tx}/pl_m}}{\sum \mathrm{int}}. \qquad (3.8)$$

The interference term is the summation of all the interference powers received from different cells, and we obtain

$$\mathrm{sinr} = \frac{\mathrm{p_{tx}/pl_m}}{\mathrm{prx_{In1}+prx_{In2}+prx_{In3}+\cdots}} \qquad (3.9)$$

Finding SINR in dB and assuming a complete pathloss compensation, α = 1, by means of (3.1)-(3.4), SINR can be written as

$$\mathrm{SINR} = \mathrm{P_0} - 10\log(\frac{\mathrm{p_0 pl_{oe1}}}{\mathrm{pl_{In1}}} + \frac{\mathrm{p_0 pl_{oe2}}}{\mathrm{pl_{In2}}} + \frac{\mathrm{p_0 pl_{oe3}}}{\mathrm{pl_{In3}}} + \cdots) \qquad (3.10)$$

Taking in mind that the power control parameters, such as P_0, are the same for all the cells, we have

$$\mathrm{SINR} = \mathrm{P_0} - 10\log \mathrm{p_0}(\frac{\mathrm{pl_{oe1}}}{\mathrm{pl_{In1}}} + \frac{\mathrm{pl_{oe2}}}{\mathrm{pl_{In2}}} + \frac{\mathrm{pl_{oe3}}}{\mathrm{pl_{In3}}} + \cdots) \qquad (3.11)$$

$$\mathrm{SINR} = \mathrm{P_0} - \mathrm{P_0} - 10\log(\frac{\mathrm{pl_{oe1}}}{\mathrm{pl_{In1}}} + \frac{\mathrm{pl_{oe2}}}{\mathrm{pl_{In2}}} + \frac{\mathrm{pl_{oe3}}}{\mathrm{pl_{In3}}} + \cdots) \qquad (3.12)$$

$$\mathrm{SINR} = -10\log(\frac{\mathrm{pl_{oe1}}}{\mathrm{pl_{In1}}} + \frac{\mathrm{pl_{oe2}}}{\mathrm{pl_{In2}}} + \frac{\mathrm{pl_{oe3}}}{\mathrm{pl_{In3}}} + \cdots) \qquad (3.13)$$

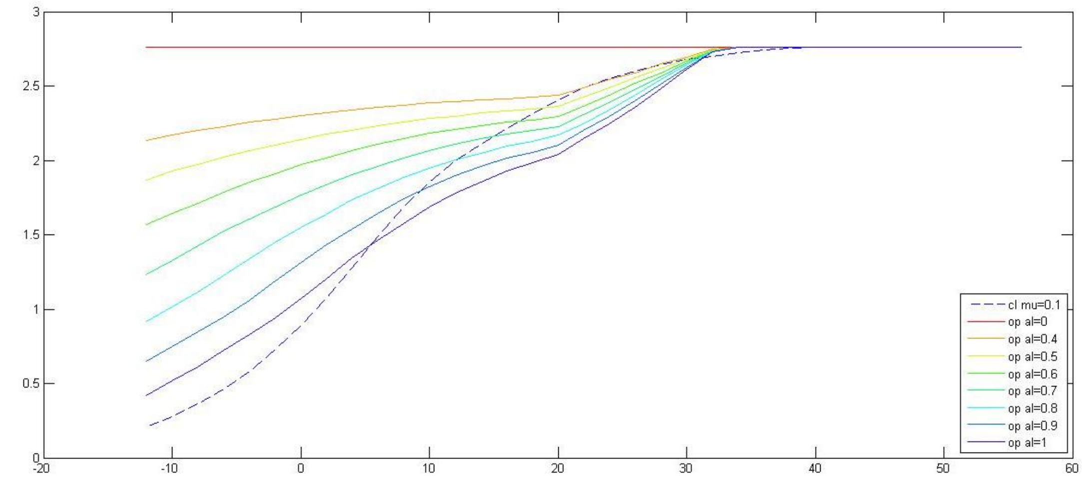
where $\mathrm{p_{tx}}$ is the transmission power, $\mathrm{pl_m}$ is main user pathloss w.r.t. its own eNB, $\mathrm{prx_{Inj}}$ is the received interference power from the interferer user which belongs to cell "j", $\mathrm{pl_{oej}}$ is the pathloss of the interfering user w.r.t. its own eNB, $\mathrm{pl_{In1}}$ the pathloss between the interfering user and the eNB interfered by it. Capital letters denote the "dB" domain while small letters denotes the linear domain.

It is now evident that, as long as the same parameters are used in all the cells, the achieved rate and the received SINR are constant and they depend on the difference of the path losses.

At the beginning, starting with a very small SINR, the interference value is very small (this can be noticed clearly with α = 1 because it corresponds to the smallest transmission power). As the main user transmission power is increased, by means of increasing the $\mathrm{SINR_{target}}$, the achieved rate is also increased until the interference becomes significant, and a constant rate state is reached. Eventually, some users saturate, reach their maximum power, and this will lead to an increase in the rate along with the increase of the main user transmission power, or $SINR_{target}$, since the difference in power between the main user and the interfering ones is not constant anymore.

The behavior of the CLPC is quite different than that of the OLPC. The reason is that every cell adjusts its power continuously and independently, in order to achieve the desired $SINR_{target}$. It is observed an almost linear increase in the achieved rate as the $SINR_{target}$ increases and this is a sign that the system is able to reach the desired $SINR_{target}$; this behavior is particularly evident at low traffic but it is also present for all the traffic values. As the $SINR_{target}$ increases, the interference also increases and the system is unable to reach the desired $SINR_{target}$: at this point the performance curve starts to approach a floor.

There is a common characteristic between the OLPC and the CLPC. There is an optimum point for the $SINR_{target}$: beyond this point any increase in the $SINR_{target}$ will not lead to an increase in the achieved rate, but it will lead to an increase in the interference, with a consequent decrease of the rate . The behavior is illustrated in Fig. 3.12, where first an increase in the $SINR_{target}$ attains an increase in the achieved rate, and then a peak is reached. Finally, a decay in the rate corresponding to an increase in the SINR is observed. Optimizing the power control technique is done by finding this particular point. At low traffic, this optimal point can be achieved with a lower $SINR_{target}$ than at higher traffic. In addition, the intensity of this behavior changes in accordance with different values of traffic and for different scenarios. In some cases this convexity effect is very clear, in others it is less evident, as shown in Figs. 3.11, 3.12.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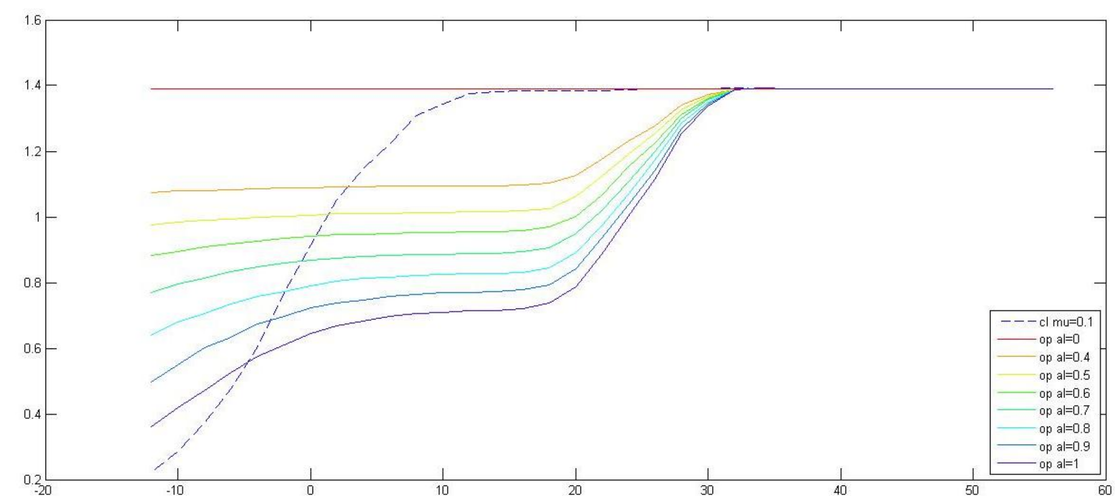
(a)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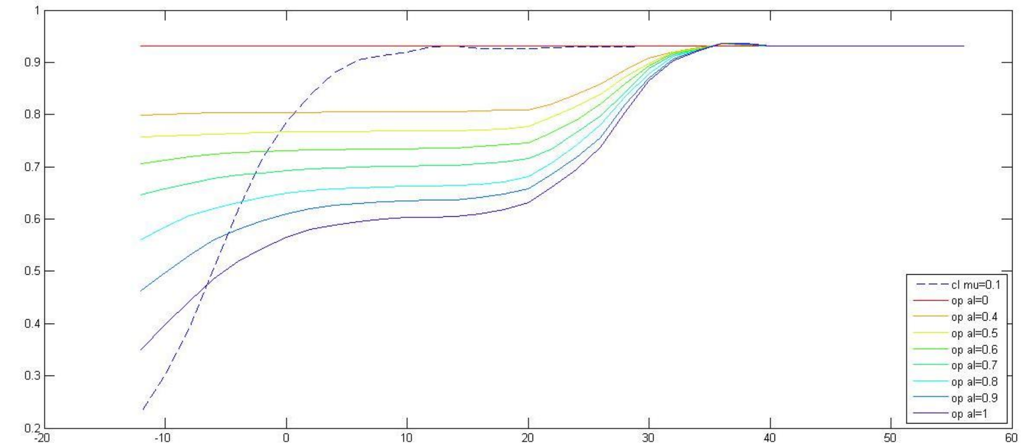

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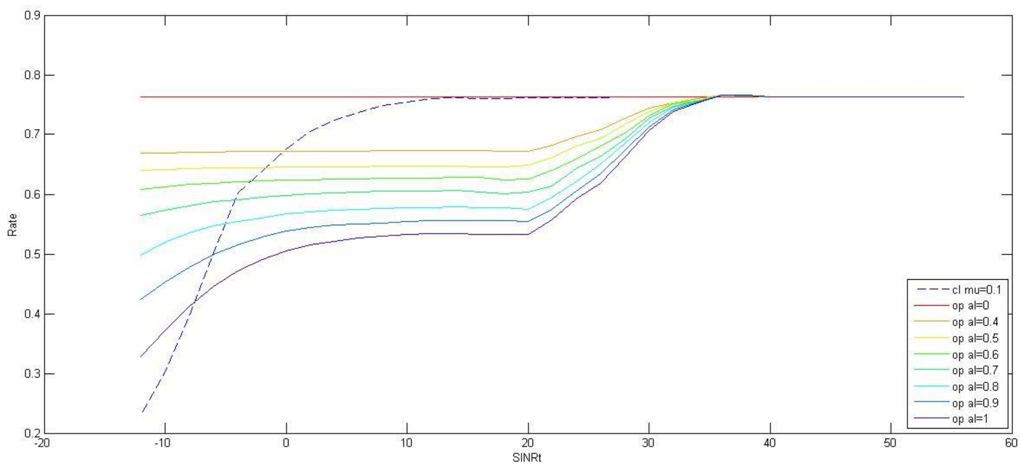
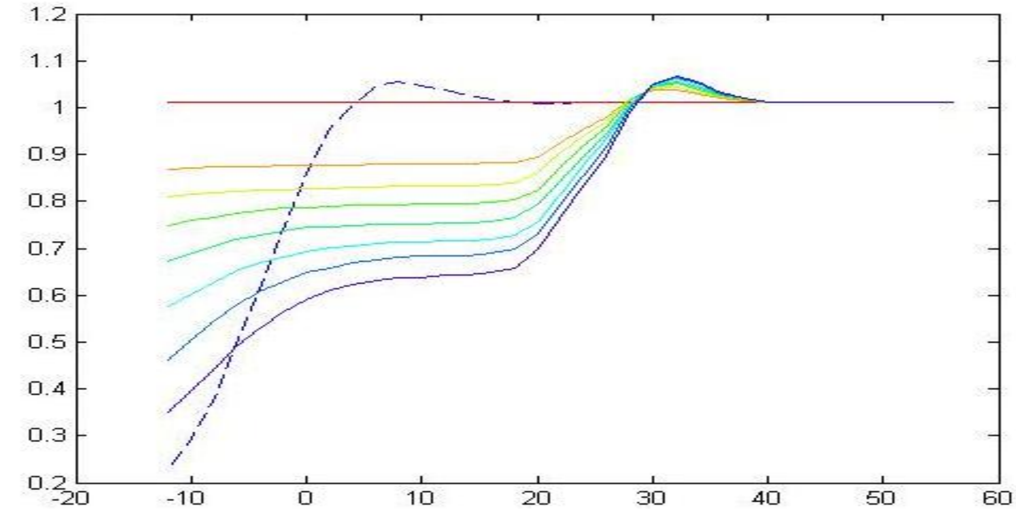


(d)

Fig. 3.11 effect of $SINR_{target}$ on the achieved rate at different values of traffic

(a) traffic = 20%, (b) traffic = 40%, (c) traffic = 80%, (d) traffic = 100%.



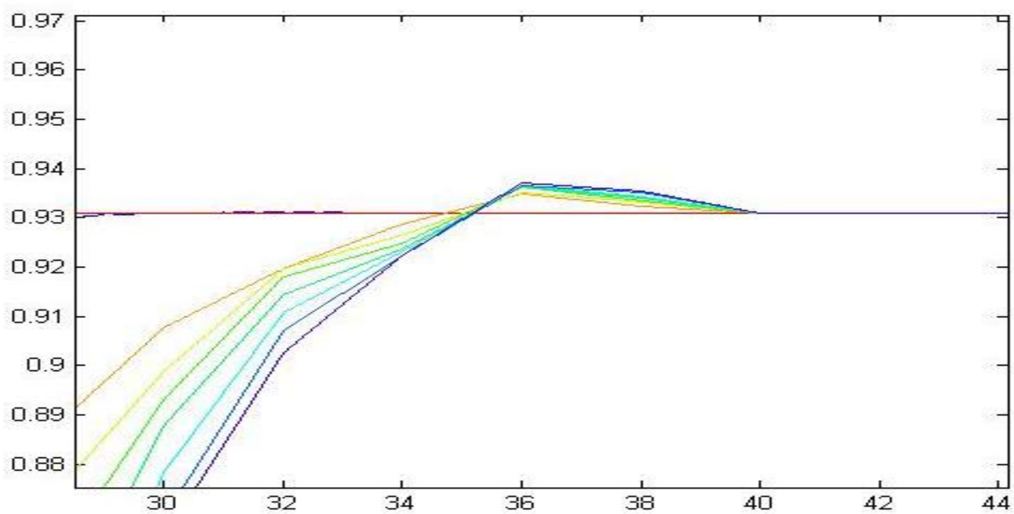
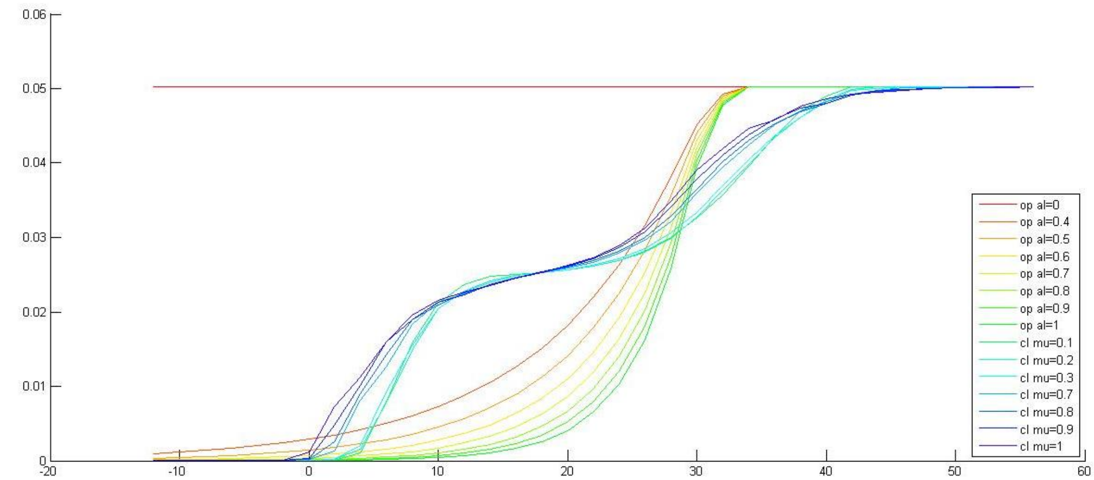


Fig. 3.12 Different examples of the convexity effect.

The next step is to compare all values of μ for CLPC against all values of α for OLPC. The comparison is done w.r.t. the transmitted power as well as the achieved rate and performance is plotted in Fig. 3.13.

The general difference in the behavior between the CLPC and OLPC remains the same for all values of μ.

For different values of μ, there is a difference in the CLPC response to $SINR_{target}$. In our simulations, the maximum achieved rate for CLPC is usually attained at smaller values of μ, typically $\mu = 0.1$. However, the difference in the maximum achieved rate between different values of μ is not too big, as seen in Fig. 3.14. On the other hand, higher values of μ achieve higher rates as well as higher transmission powers at lower values of $SINR_{target}$ (this behavior can be observed at Figs. 3.13, 3.14.



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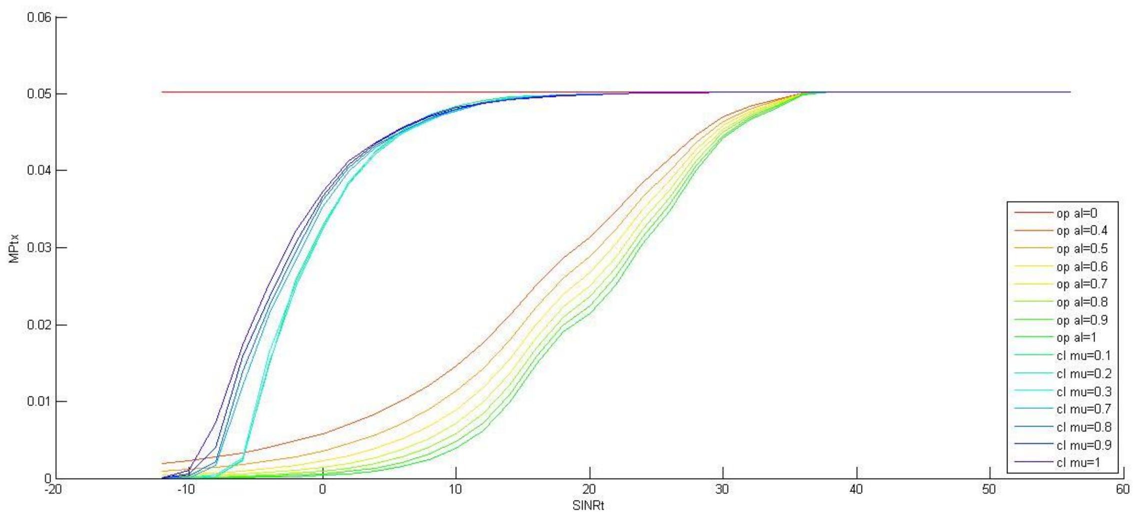
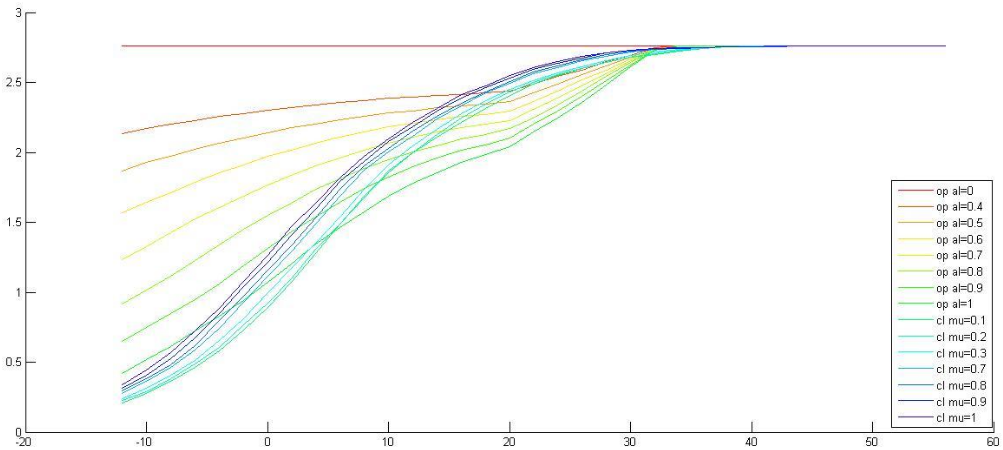
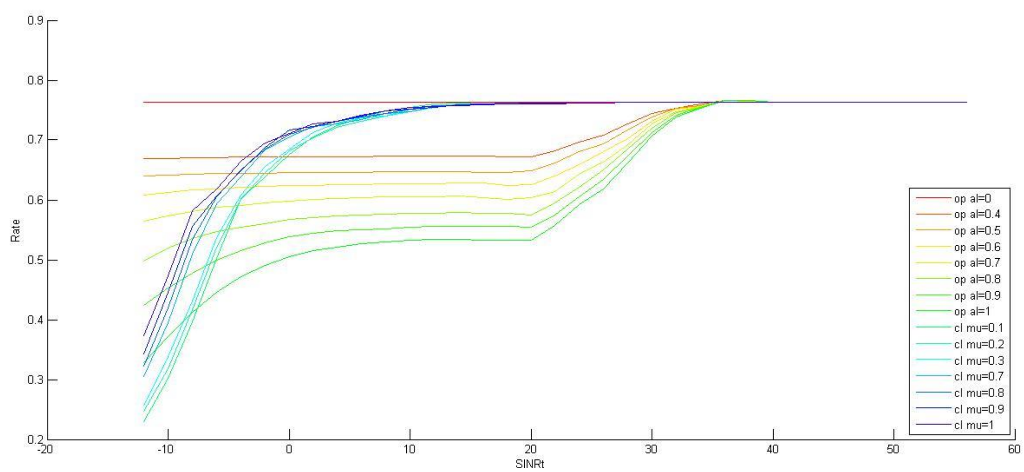


(b)

Fig. 3.13 Effect of $SINR_{target}$ on MP_{Tx} for the full range of α for OLPC, and of μ for CLPC at different traffic percentages (a) traffic = 20%, (b) traffic = 100%



(a)



(b)

Fig. 3.14 Effect of $SINR_{target}$ on the achieved rate for the full range of α for OLPC, and of μ for CLPC at different traffic percentages (a) traffic = 20%, (b) traffic = 100%

3.7.3 Effect of α in CLPC

Since the CLPC algorithm runs around the OLPC operating point, it is worth looking into the effect of α in CLPC.

As it can be seen in Fig. 3.15, changing α has a very small impact on the performance of the CLPC, and the effect gets smaller as the $SINR_{target}$ increases. This happens because α determines only the starting point but the final performance is driven by the $SINR_{target}$, since the CLPC always adjusts the UE used transmission power to achieve this $SINR_{target}$.

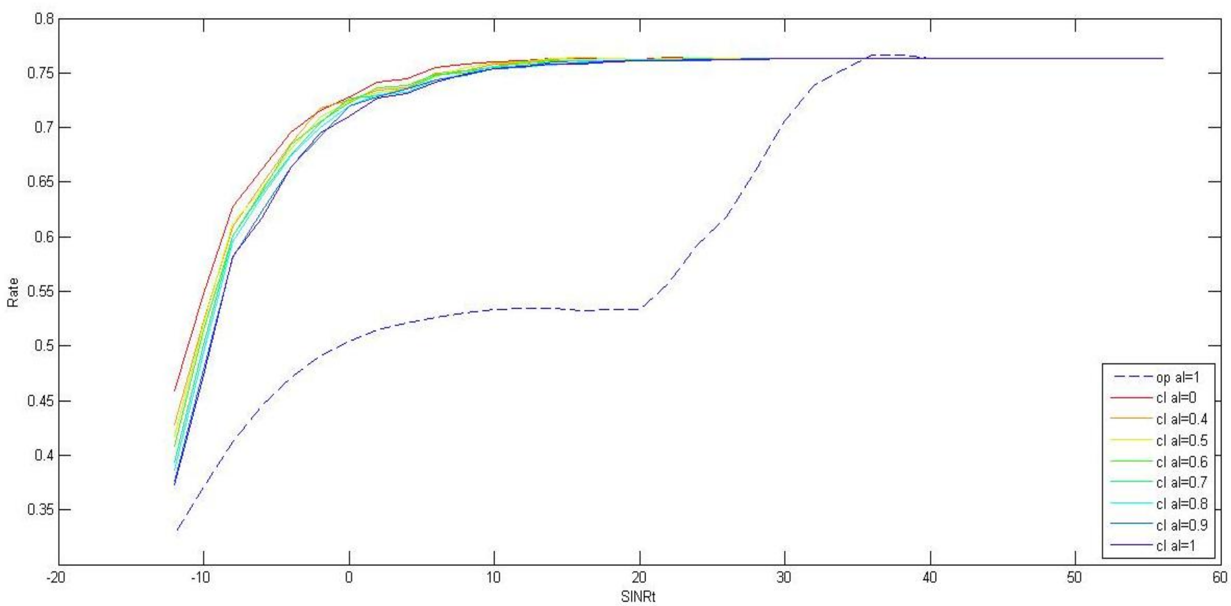


Fig. 3.15 Effect of $SINR_{target}$ on the achieved rate for the full range of α for CLPC.

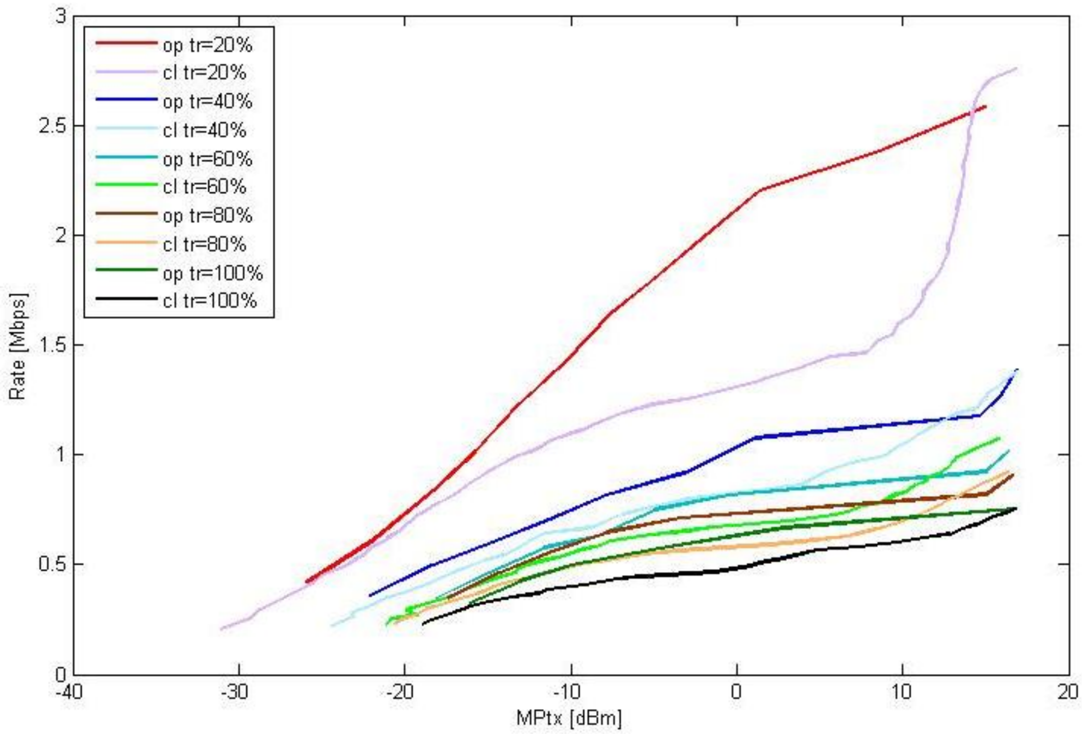


Fig. 3.16 Minimum power for achieving the rate (tr = traffic percentage).

3.7.4 The minimum power for achieving a rate

In an effort to find the relation between the transmitted power and the achieved rate, for the two power control techniques, OLPC and CLPC, the relation between the minimum transmission power required to reach a certain rate subset was plotted.

The entire possible achievable rate range, for the tested system with all the possible parameters, by OLPC or CLPC, was stored. Then it was sorted from the minimum to the maximum and divided into small subsets. For each subset, the minimum power that can achieve any rate within the subset was selected. This procedure was repeated for different values of traffic for both OLPC and CLPC.

For most of the rates, at a given transmission power “MP_{Tx}” the OLPC is capable of achieving higher rate than the CLPC, but at the highest rates the CLPC performs better than OLPC. At full traffic, 100%, the CLPC is unable of passing the OLPC. However, they intersect at the maximum point and this behavior is illustrated in Fig. 3.16.

3.8 Impact of random traffic in outer cells (RATR)

One of the tested scenarios is RATR, where the number of allocated RBs per user is changed every TTI. When targeting maximum rate, the system and the UEs are working close to the maximum power. The UE power is distributed amongst its available RBs and changing the number of allocated RBs changes the amount of power per RB, which also changes the value of the generated interference. This creates a semi-fast fading condition and, of course, the behavior of the power control techniques under this condition will be slightly different from the original one. In the following, some of the important tests will be repeated for the RATR.

3.8.1 Optimal parameters for maximum average rate

An extensive simulation campaign was performed with all the possible combinations of the power control parameters. The simulations were done for the OLPC and CLPC at different percentages of traffic. The parameters that achieve the maximum average rate were recorded and reported in Table 3.8, similarly to Tables 3.4, 3.5, in Sect. 3.6; here the cell radius used is 250 m.

Max Avg. Rate	P_{Tx} [dBm]	Closed/ Open	Alpha	SINR	μ	Traffic percentage
1.7209	17.0103	op	1	28	-	20
1.8764	15.5286	Cl	0	10	0.1	20
0.8412	16.6312	op	1	26	-	40
1.0240	14.9682	Cl	0.4	2	0.1	40
0.7826	16.9662	op	1	36	-	60
0.8132	11.3621	cl	0	-2	0.1	60
0.7281	16.9772	op	1	36	-	80
0.7325	16.5062	Cl	0	4	0.1	80
0.7343	16.9864	op	0.9	36	-	100
0.7369	16.9664	Cl	0	10	0.1	100

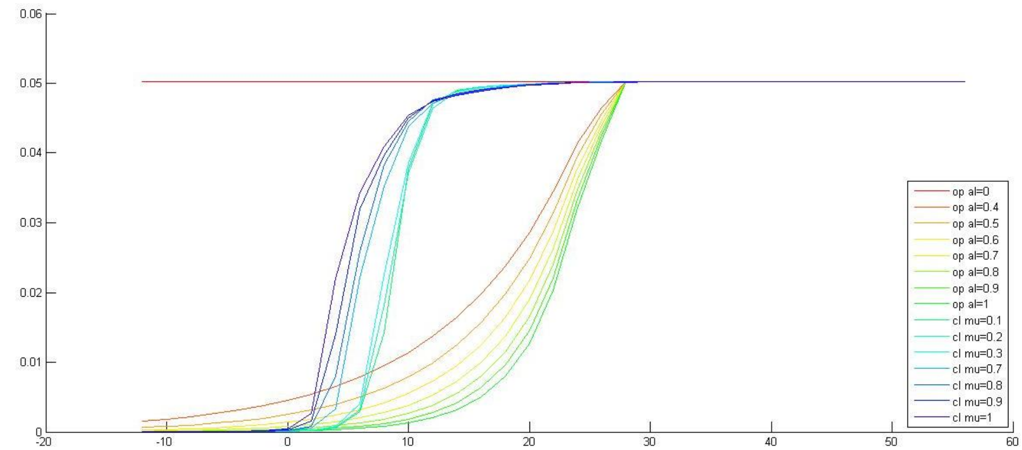
Table 3.8 Highest average rate achievable by OLPC and CLPC at different values of traffic, using RATR.

The first thing to be noticed is that the achieved rate is less than that of the original scenario. This is expected since now the channel is under constant change, and the RBs are subject to higher values of interference, with powers up to the full P_{max} per RB.

Secondly, the CLPC, under RATR condition, is better than the OLPC, even under low traffic. That is because CLPC tries to adapt the transmission power according to the channel state. Since the channel is under constant change, the CLPC turns out to be more efficient in performing the power control task under these conditions.

3.8.2 Impact of target SINR

The evolution of the achieved rate and the transmission power changing $SINR_{target}$ was also tested. The general system behavior is still the same even if some minor differences can be noticed in Figs. 3.17, 3.18.



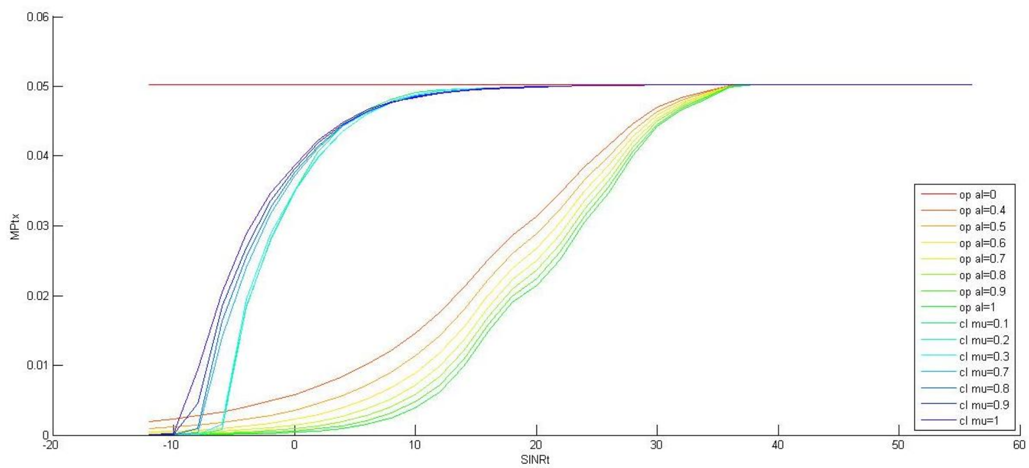


Fig. 3.17 Effect of $SINR_{target}$ on MP_{Tx} for the full range of α for OLPC, and of μ for CLPC at different traffic percentages (a) traffic = 20%, (b) traffic = 100% .

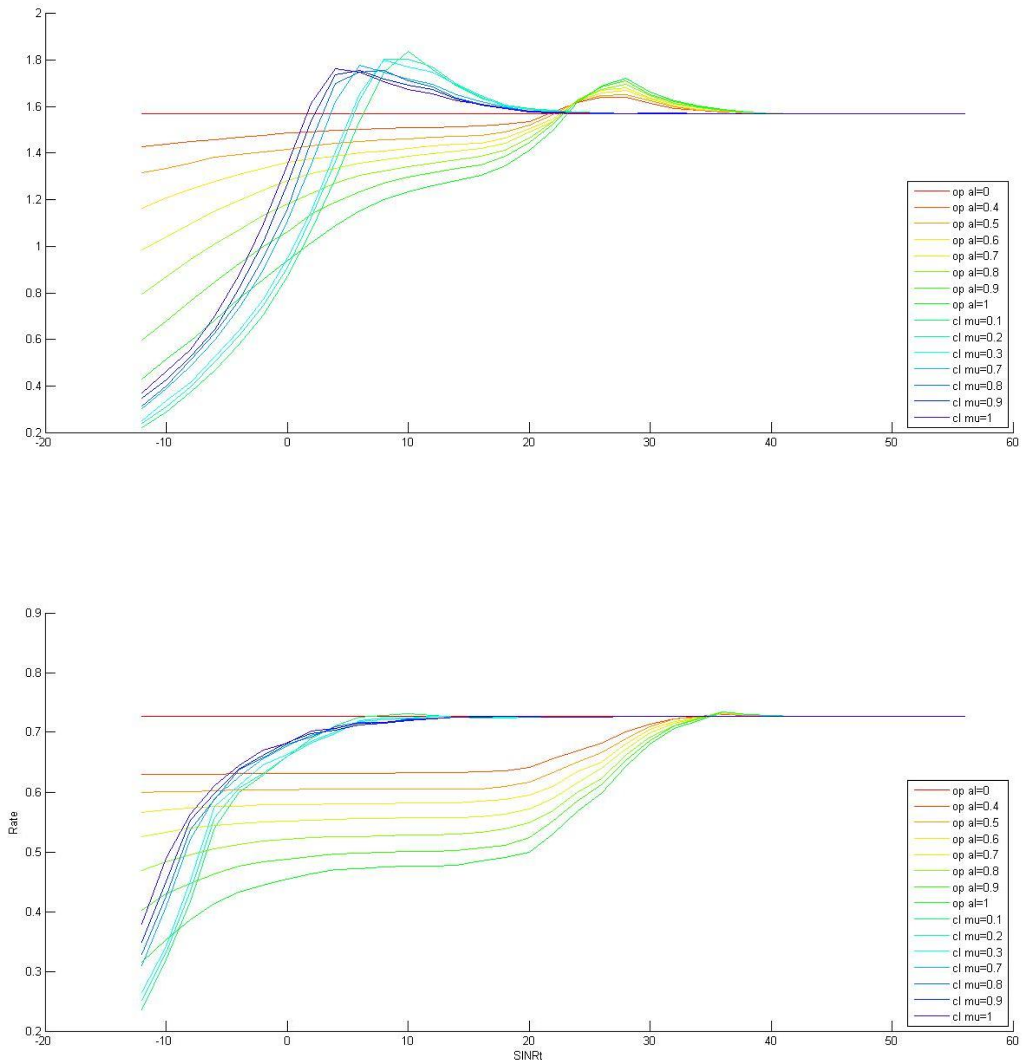


Fig. 3.18 Effect of SINRtarget on the achieved rate for the full range of α for OLPC, and of μ for CLPC at different traffic percentages (a) traffic = 20%, (b) traffic = 100%.

3.9 Conclusions

In this chapter a complete study for the conventional power control techniques has been provided, using mainly simulations. We have discussed the following main results:

1. The difference in the performance between the OLPC and CLPC, w.r.t. the maximum achievable rate, is not too big.
2. There is a tradeoff between average cell rate, and cell edge users' rate. If it is needed to have a high average cell rate, the cell edge users' rate will be low with a great difference between cell center users and cell edge users. On the other hand, if the goal is to achieve the highest possible cell edge users' rate, the price will be a reduction in the overall cell rate, compared to the previous case.
3. Although the evolution with SINRtarget is different, both techniques consume similar amount of power to achieve the maximum achievable rate. This consumed power is very close to Pmax, i.e. very high.

In the next chapter, a hybrid technique will be introduced, investigated and compared to the conventional techniques. The goal of the hybrid technique is to achieve a good cell edge users' performance, with a limited sacrifice in the average cell rate.

Chapter 4
Hybrid power control

4.1 The motivation behind hybrid power control

As stated in the previous chapter, there is a fundamental limit in the conventional power control techniques; having a high cell rate at the expense of the performance of cell edge users, or having a moderate cell edge users performance at the expanse of average cell rate performance.

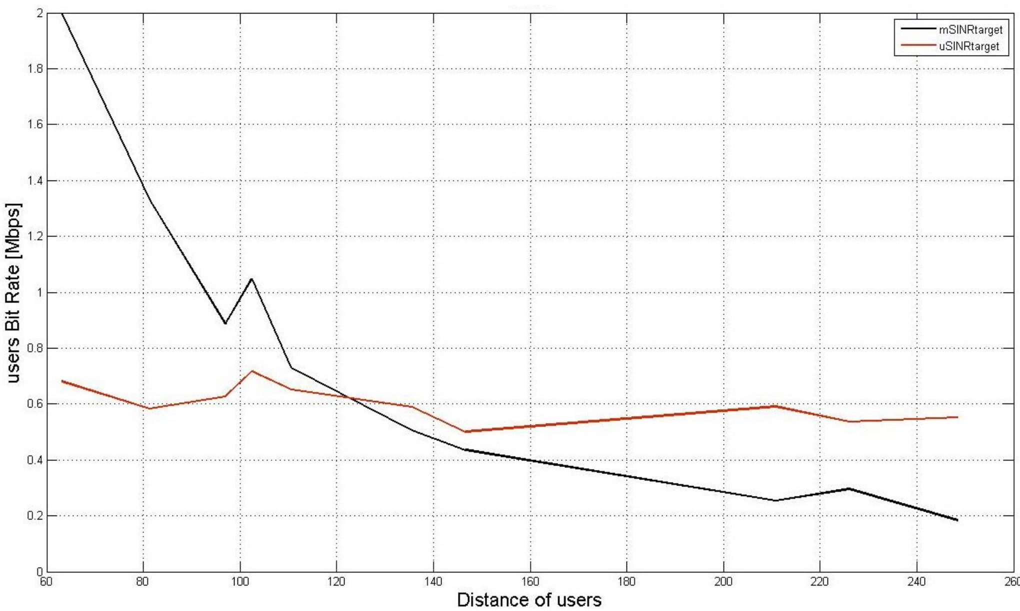
In order to overcome this problem, some modifications have been done to the conventional power control techniques [14, 17]. As a result, an improvement was observed in the performance of the system. This improvement in some cases was too small, in other cases there was a reduction in the average cell rate, and, even more, no improvement in the power consumption was achieved. In the following, we introduce the hybrid power control (HPC). Using HPC will allow an improvement in cell edge users' rate, a major reduction in the power consumption, and an improvement in the average cell rate.

In the next Sections, an introduction to the HPC will be presented, along with the idea behind it. Later, a study on the HPC performance is going to be presented with several simulations and illustrative figures.

After performing the simulations for the conventional CLPC and OLPC, it is noticed that according to users' pathloss there are two users groups, with different behavior, with respect to the used transmission power and power control technique. From Figs. 4.1, 4.2, we can make the following two observations.

1- Let us focus on two important values of $SINR_{target}$. The first one is $uSINR_{target}$, which is the $SINR_{target}$ that attains the maximum uniform behavior; as $SINR_{target}$ is increased, the achieved rate remains the same for all users and all users are able to achieve the selected $SINR_{target}$, until a certain $SINR_{target}$ is reached, the $uSINR_{target}$, and any $SINR_{target}$ beyond this value will lead to a loss of the uniformity and to a reduction in the cell edge users rate. The other important $SINR_{target}$ is $mSINR_{target}$, which is the $SINR_{target}$ responsible of achieving the maximum average cell rate, characterized by a high cell center rate and low cell edge rate. Considering the results of the two $SINR_{target}$s together, in Fig. 4.1, it can be observed that there is a group of users having their rate at the $mSINR_{target}$ less than their rate at the $uSINR_{target}$, and the other group of users having the $mSINR_{target}$ rate higher than the $uSINR_{target}$ rate.

2- Since several scenarios were carried out to test the performance of the PC techniques, it was found that in some of these scenarios the OLPC is better for CC users (these users attain their best performance when the OLPC is used in the cell) and CLPC better for CE users. Furthermore, if the channel has not severe fading and the interference state does not change significantly, then OLPC is more favorable to be used, since the CLPC requires sending feedback. Usually CC users, because of their small distance w.r.t. the eNB, fulfill these conditions and OLPC might be a suitable choice for them.



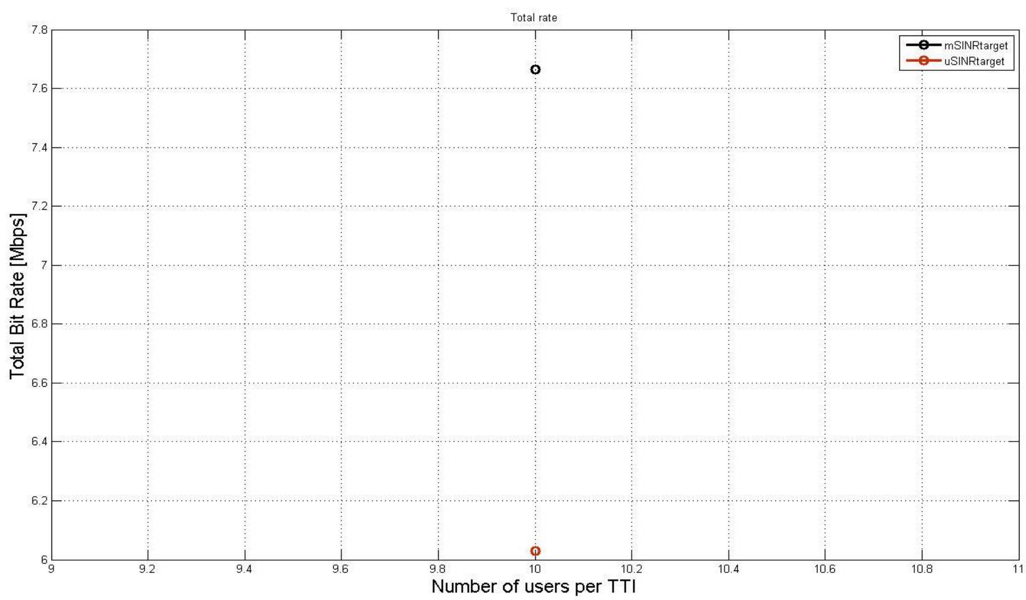
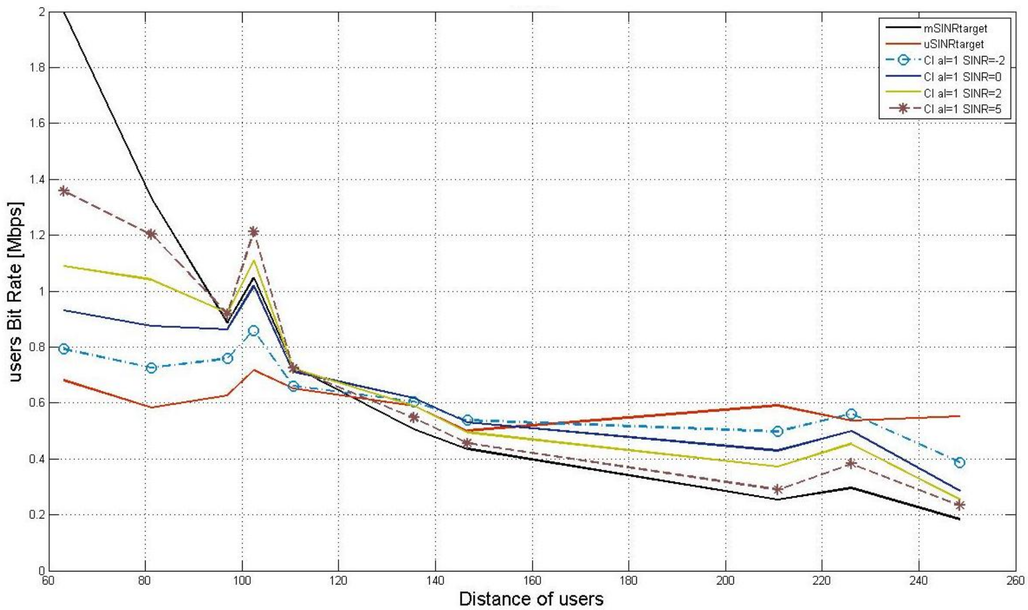


Fig. 4.1 Achieved bit rate per user and total achieved rate for $mSINR_{target}$, and $uSINR_{target}$.



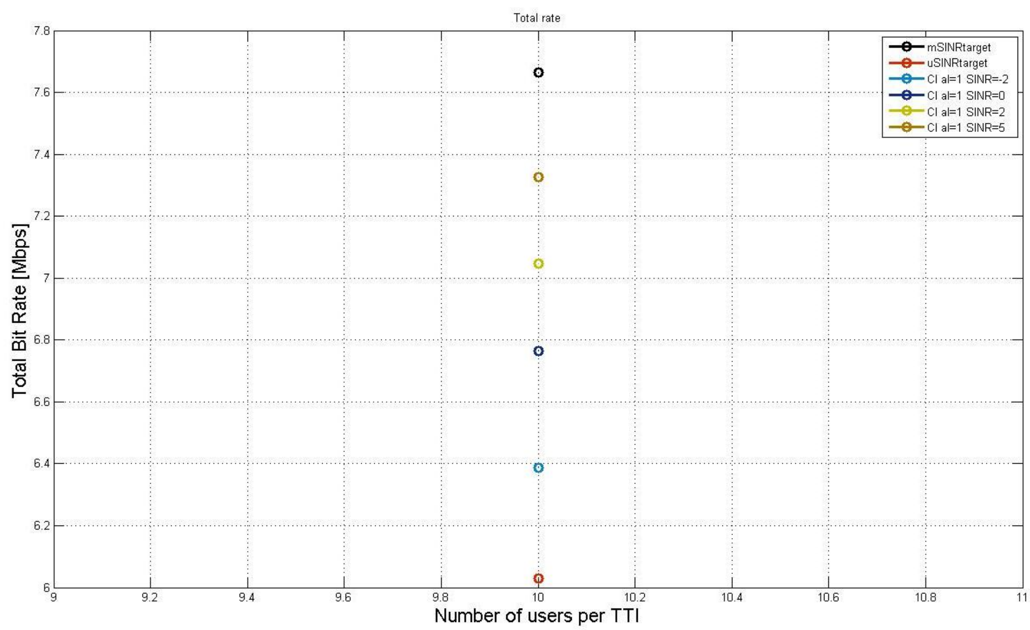


Fig. 4.2 Effect of increasing $SINR_{target}$ on the achieved rate per user, in comparison with $mSINR_{target}$, and $uSINR_{target}$.

In order to clarify further the first point, let us consider Fig. 4.2 : as $SINR_{target}$ is increased above $uSINR_{target}$, a splitting in the cell performance can be noticed, i.e. CE users achieved rate starts to decrease, while CC users achieved rate starts to increase. In other words, a low $SINR_{target}$ generates a uniform rate for the whole cell and, as $SINR_{target}$ is increased, an uniform increase in the rate for the entire cell is attained till to $uSINR_{target}$; after $uSINR_{target}$ the CE users achieved rate will start to decrease and that of CC users will keep increasing.

The idea derived from these two observations was the following: the users within the cell are divided into two or more groups, each group is selected according to the pathloss w.r.t. the serving eNB, each group has a different $SINR_{target}$ and a different maximum achievable rate. Each group performance is affected and limited by three factors:

1. transmission power of users who belong to the same group but in the other adjacent cell, i.e. users occupying the same position or having similar distances to their own eNB in the other adjacent cells.

2. Transmission power of users who belong to different groups in the other adjacent cells.

3. Its own position, pathloss or distance w.r.t. the serving eNB.

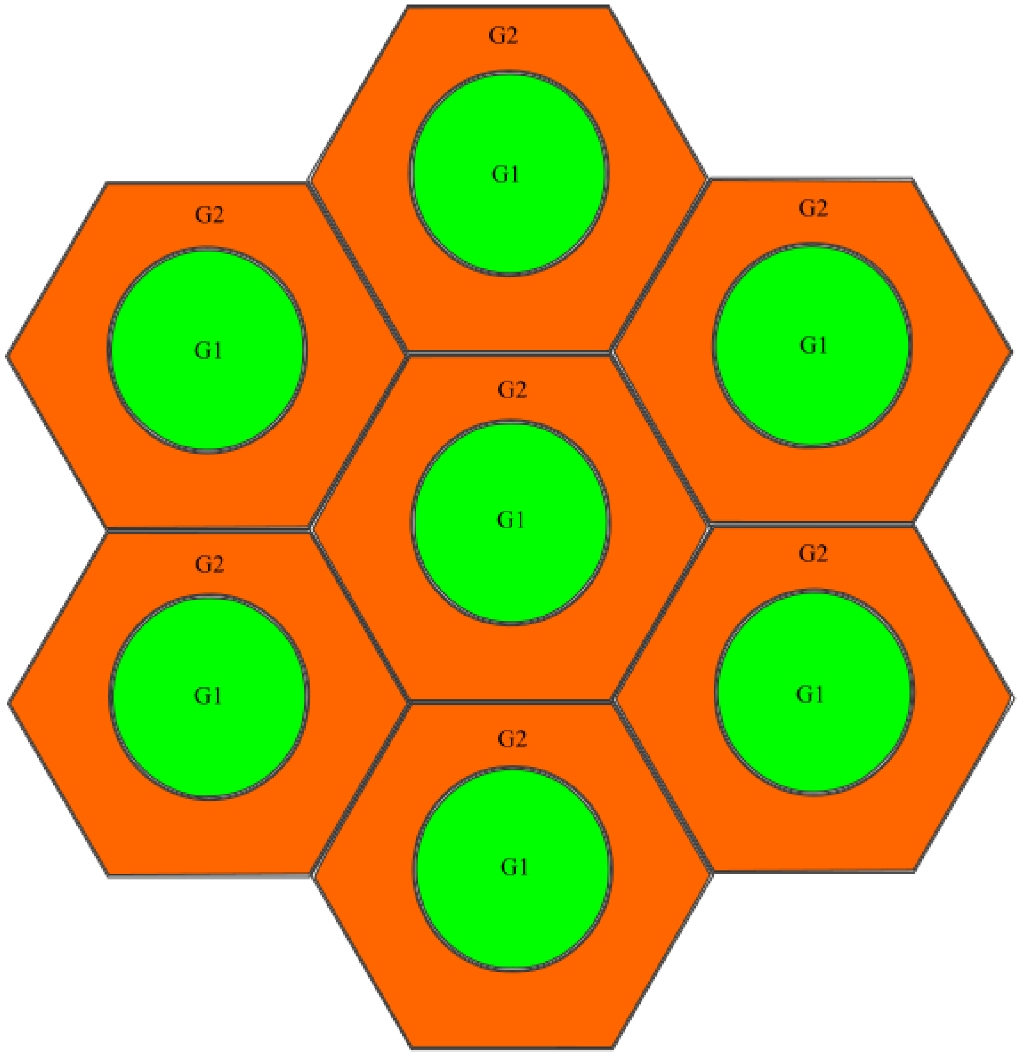


Fig. 4.3 Dividing the cells into groups, G1 and G2.

Starting from the cell edge, the CE users, or group, are highly affected by these three factors, even if the first factor is the dominant one. As the pathloss decreases, moving from CE toward CC, the second factor becomes more dominant than the first one and the effect of all the three factors gradually fades.

Thus, in our point of view, the cell contains several groups and the members of these groups share, more or less, the same capabilities, achievable rate and vulnerability to interference. Each of these groups has a maximum achievable rate regardless of their maximum allowed power, and regardless of the existence of the other groups, i.e. regardless of the existence of different groups in the other adjacent cells. This means that these users cannot target some rates and trying to force them to achieve the same rate of other, different groups, would just lead to an increase of interference and hence a reduction in the performance and waste of transmitted power. By dividing the cell into more groups, the performance can approach the optimal performance in terms of rate, interference and power consumption. By using fewer groups, the resulting solution is clearly sub-optimal.

In a few words, because each group has different capabilities, and is affected differently by the given factors, the system should not try to make all the users target the same SINR, because some of them would not be able to achieve it. This simple principle is one of the main motivations for considering the implementation of a hybrid technique that uses different techniques for each group and different $SINR_{target}$. An example of the cell groups is illustrated in Fig. 4.3 and in this example the cells are divided into two groups (G1, and G2), characterized by similar pathloss to the serving eNB.

In order to further inspect this theory, the cell was divided into two groups CC, and CE. The limit, i.e. the maximum achievable rate, was inspected for each group, independently of the other group, as in Figs. 4.4, 4.5.

The CE group was tested while giving the users of the CC a zero transmission power (Fig. 4.4). The observed behavior is only for the CE users in all the system cells, i.e. the observed performance will be only due to CE users. First a very small $SINR_{target}$ was used and then it was increased for observing the system reaction: at the beginning the achieved rate starts to increase according to the increase of $SINR_{target}$. At a certain $SINR_{target}$, the CE users reached their maximum rate, not high even though there are no CC users. Any additional increase of the $SINR_{target}$ beyond that will lead to a decrease in the achieved rate for the CE users, i.e. more transmission power and less performance. This behavior is illustrated in Fig. 4.6.

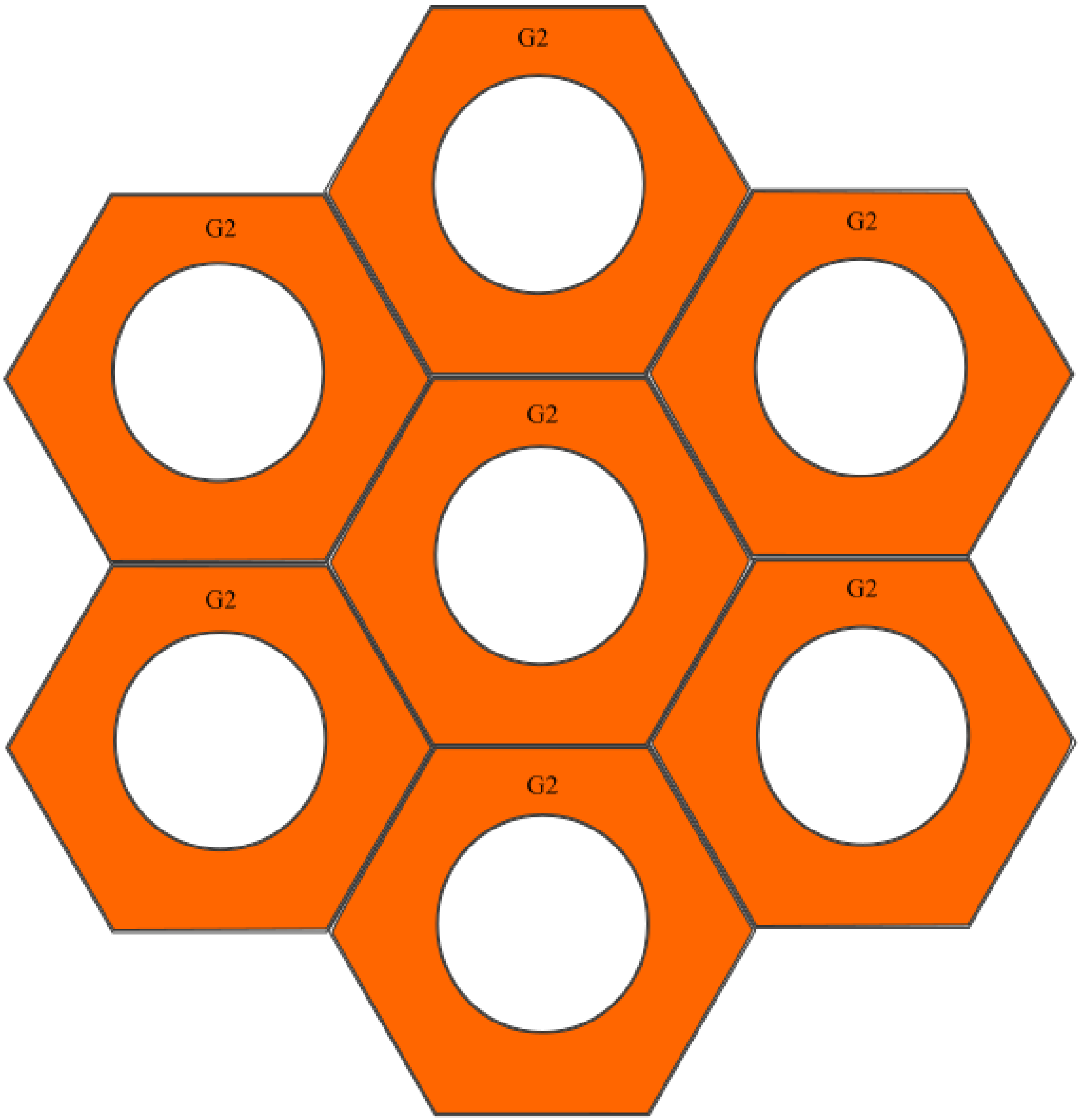


Fig. 4.4 Cells having only CE users, G2.

The same procedure was repeated for CC users, canceling the CE users and observing the behavior of CC users as a function of target SINR, as illustrated in Fig. 4.5.

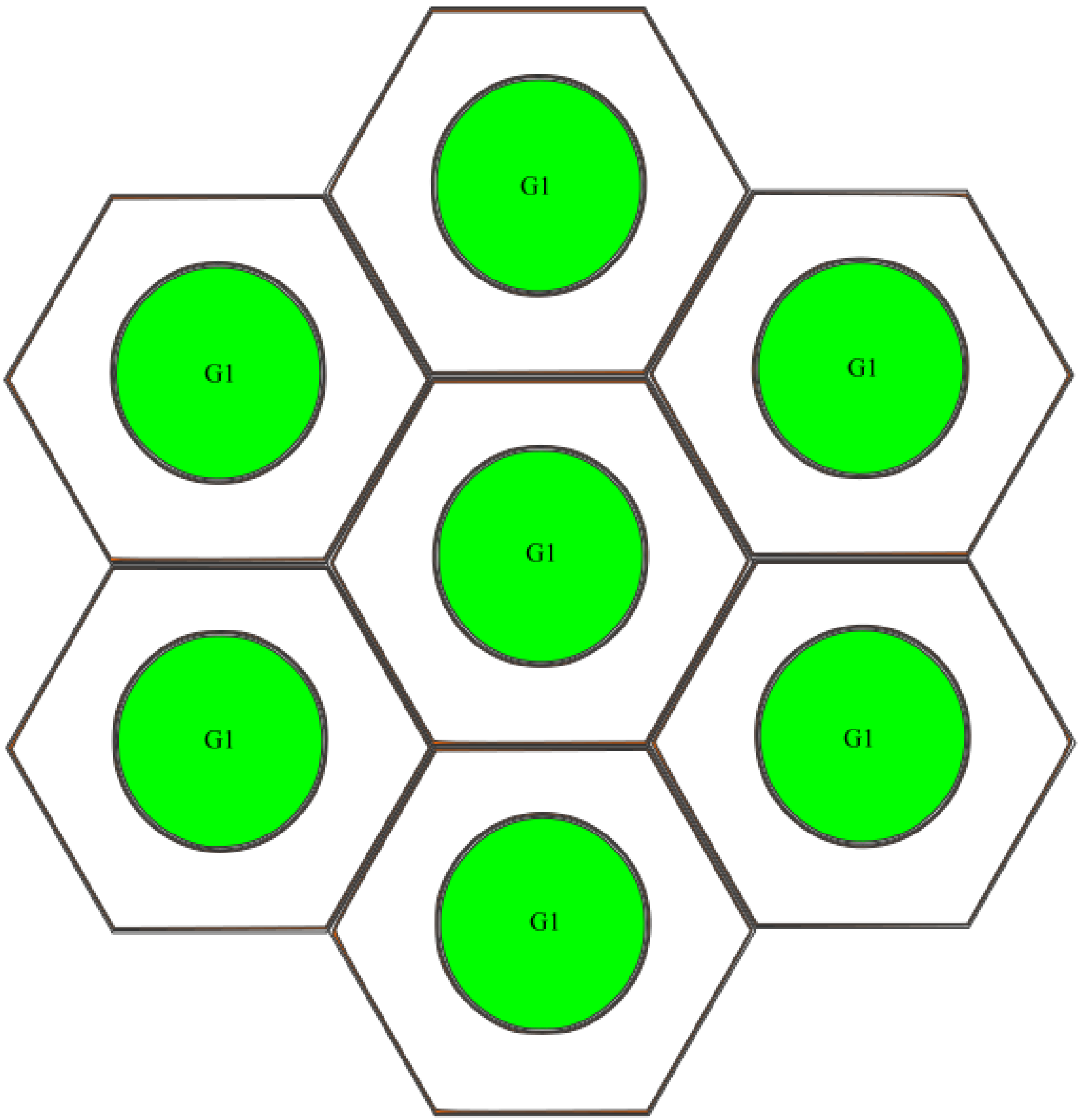


Fig. 4.5 Cells having only CC users, G1.

The behavior of the CC has two crucial differences w.r.t. the CE ones (Fig. 4.7):

1- the achieved rate and the optimal $SINR_{target}$, at with performance starts to decay, is higher than that of CE;

2- After reaching the optimal $SINR_{target}$, any further increase in the $SINR_{target}$ does not lead to a decrease in the rate, but to a saturation; a point reached with an increasing $SINR_{target}$ has no effect, neither positive nor negative on the CC users.

It can be observed that the behavior of CE users is due mainly to two reasons:

1- the most important is that CE users are primarily limited by other cells CE users, even without having CC users in the system, and any attempt to increase their power beyond a certain, not very high, point will lead simply to an increase of the interference. In other words, CE users are also the main source of interference and the most affected by it.

2- Another factor is that CC users have a smaller pathloss and consequently most of their power is exploited for achieving the rate. On the other hand, CE users have a higher pathloss and most of their power is used to compensate the pathloss, and they cannot achieve a very high rate due to maximum transmission power constraints.

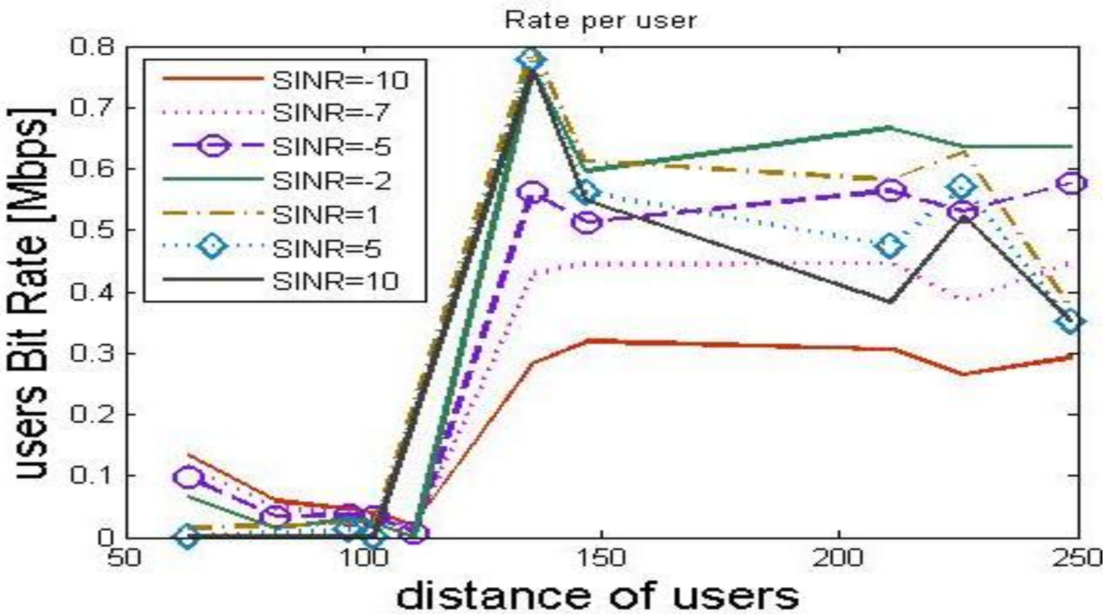


Fig. 4.6 Effect of increasing $SINR_{target}$ for CE users, while fixing that of CC users at a very low value.

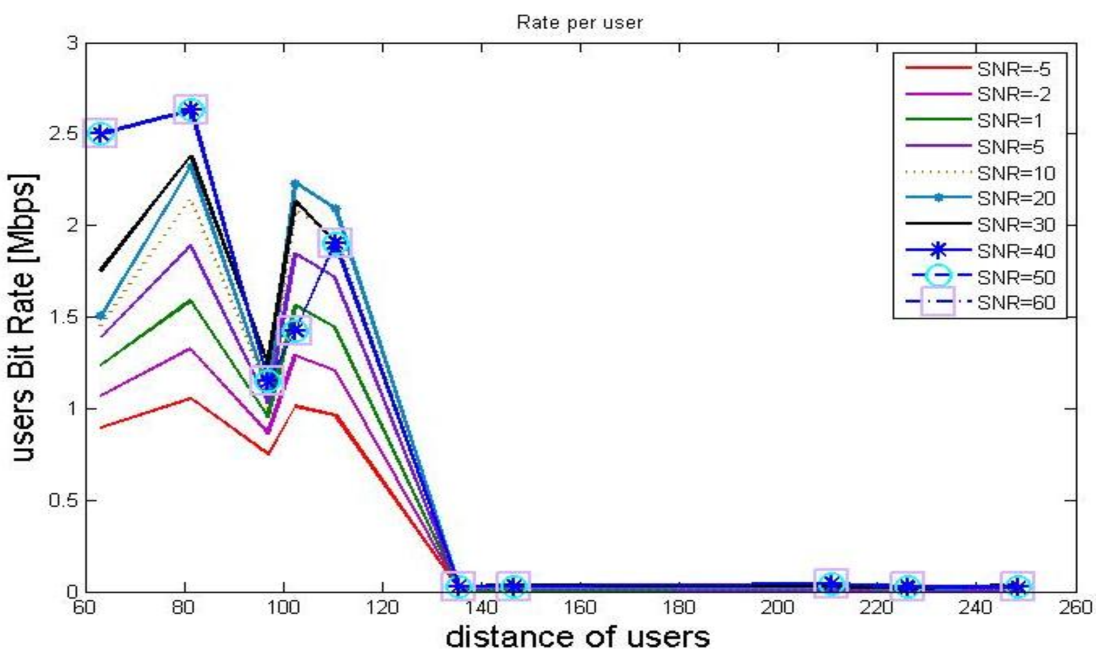
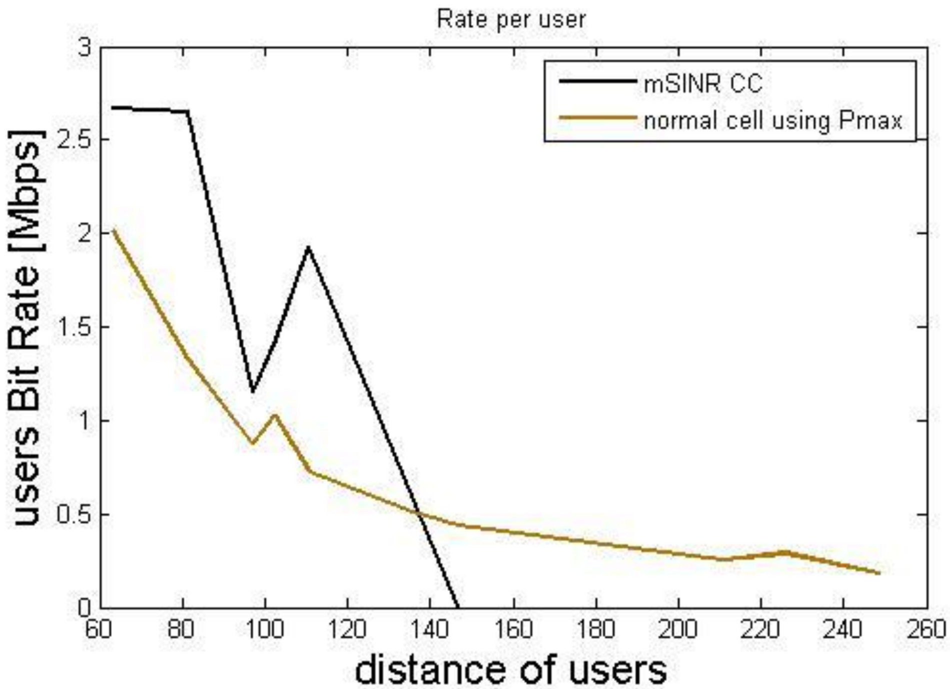


Fig. 4.7 Effect of increasing $SINR_{target}$ for CC users, while fixing that of CE users at a very low value



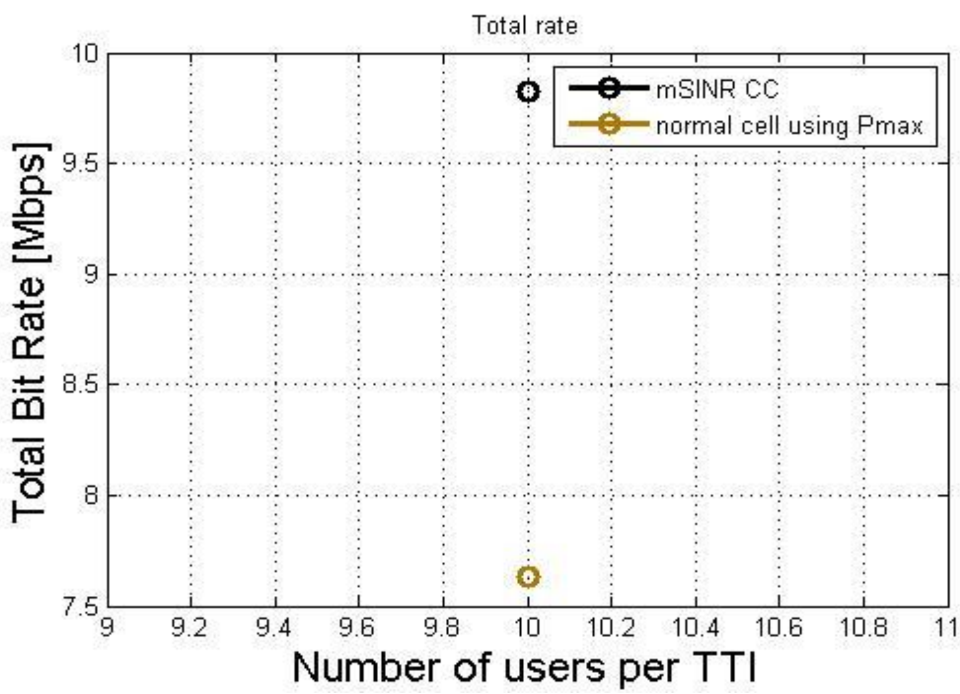
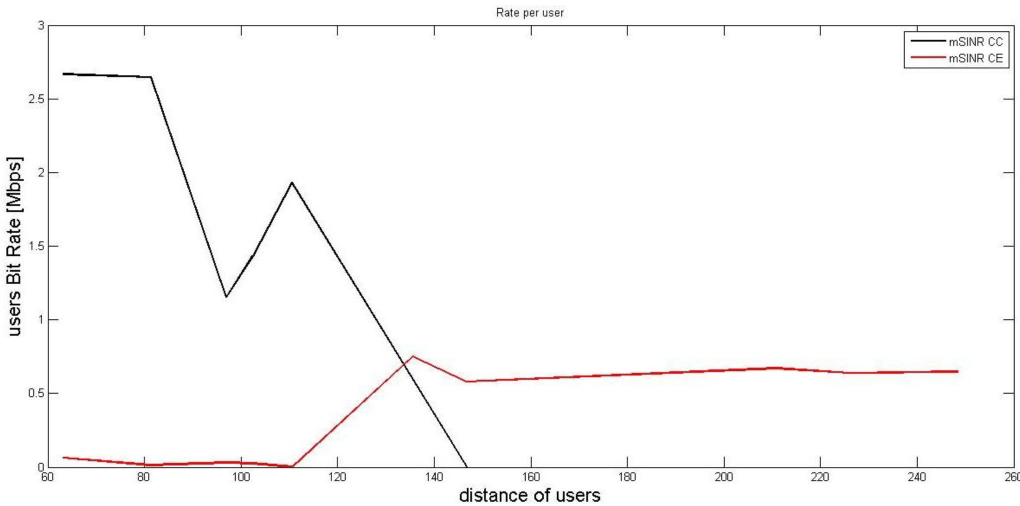


Fig. 4.8 Increase in the maximum achievable rate for CC users by canceling CE users and using maximum power, in comparison with using maximum power in a cell without cancelling CE users.



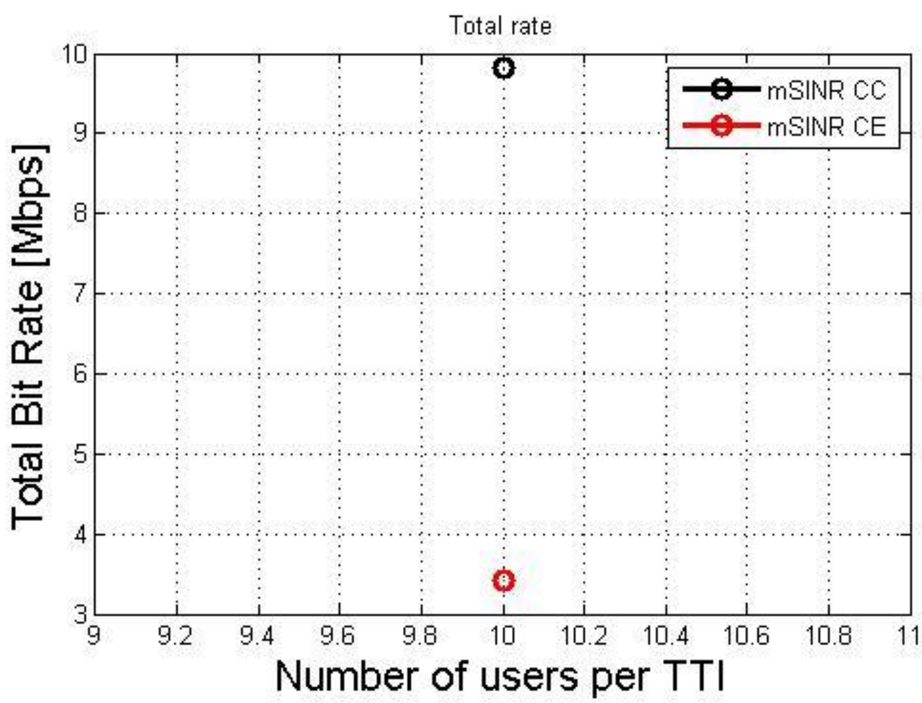


Fig. 4.9 Difference between the rate limit for CC and CE users and their performance.

From this investigation, it can be concluded that CE users have a rate limit which is lower than that of the CC users. Trying to achieve a higher rate by using more power or $SINR_{target}$ will lead to a waste of power and increase in the interference without any advantage. Furthermore, there is no meaning to give the CE users the same $SINR_{target}$ as the CC users because they belong to two different groups with different capabilities. It is also worth noting that this rate limit is independent of the maximum allowed power for the UE, i.e. hypothetically assuming unlimited power in the UE will not change the result, which means that the limit is mainly determined by interference.

Now it is clear that using one $SINR_{target}$ for the whole cell leads to a critical scenario: choosing a high $SINR_{target}$ and achieving high average cell rate, due mainly to the potential of CC users but with bad performance of CE users or choosing a low $SINR_{target}$, optimal for CE group, and losing the high average cell rate of CC users. In fact, this tradeoff was investigated in several papers in the literature: optimizing the $SINR_{target}$ can be done for obtaining high average cell rate or high CE performance.

As a result of this investigation, it was decided to use the hybrid approach (HPC), splitting the cell into two groups according to the pathloss and giving each group a different $SINR_{target}$ and different target rates. Furthermore, the possibility of giving each group a different technique, OLPC or CLPC, is taken into account.

The HPC was implemented for different combinations:

1- OLPC for CC and CLPC for CE (op-cl),

2- OLPC for CC and OLPC for CE (op-op),

3- CLPC for CC and CLPC for CE (cl-cl).

The HPC performance and performance of each combination varies with the different scenarios. The op-cl is always better than the conventional power control technique, in terms of the average rate, CE users' rate, and especially the power consumption, which is always better than in the conventional techniques.

Performance of the different HPC combinations is evaluated for different scenarios and presented in the next Sections.

4.2 HPC performance

The HPC performance is evaluated here for different combinations and for different splitting pathlosses, where the splitting pathloss (PLS) is the pathloss that divides the cell into CC and CE. In this Section, the potential gains of the HPC are illustrated by means of simulations. However, in the next chapter a detailed study of PLSPLS selection and of the optimal PLSPLS that achieve energy saving and rate gain will be provided.

4.2.1 Using different PLS values for the op-cl combination

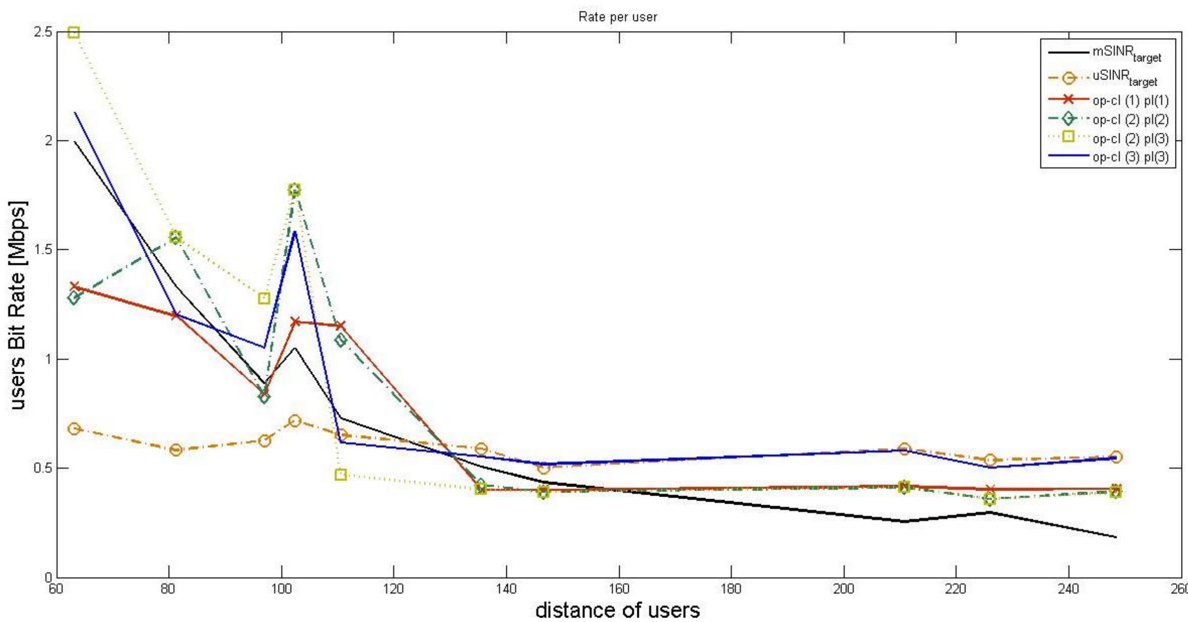
In general, the best HPC combination is the op-cl. Since the CE users are in a critical position, with a high interference environment, they need the CLPC as a countermeasure against the change in their performance. On the other side, the CC users, in general, are in a better situation than the CE ones and they can use OLPC for achieving good performance without the need of CLPC signaling.

Performance of op-cl at different values for PLSPLS is illustrated in Figs. 4.10, 4.11. It is noticed that not all the PLS values achieve the same performance and using a correct PLS value is important for a very good improvement in the system performance. In particular there are two interesting cases:

1. The first case is the op-cl3. The CE group achieves better performance than with $mSINR_{target}$, and there is about a 2.3 Mbps increase in the total cell bit rate with an overall power consumption reduced by 22 dB.

2. The second case is the op-cl4. The CE group achieves the same performance as the $uSINR_{target}$, the CC group performance is a little better than that of $mSINR_{target}$ and there is an improvement in the achieved rate of almost 2 Mbps with a power consumption reduced by 17 dB.

It is now evident the advantage of HPC. By using CLPC for the CE users and using a target SINR below the limit of the CE, an important reduction in the consumed power can be achieved, respecting the desired target rate and controlling the interference due to CE users.



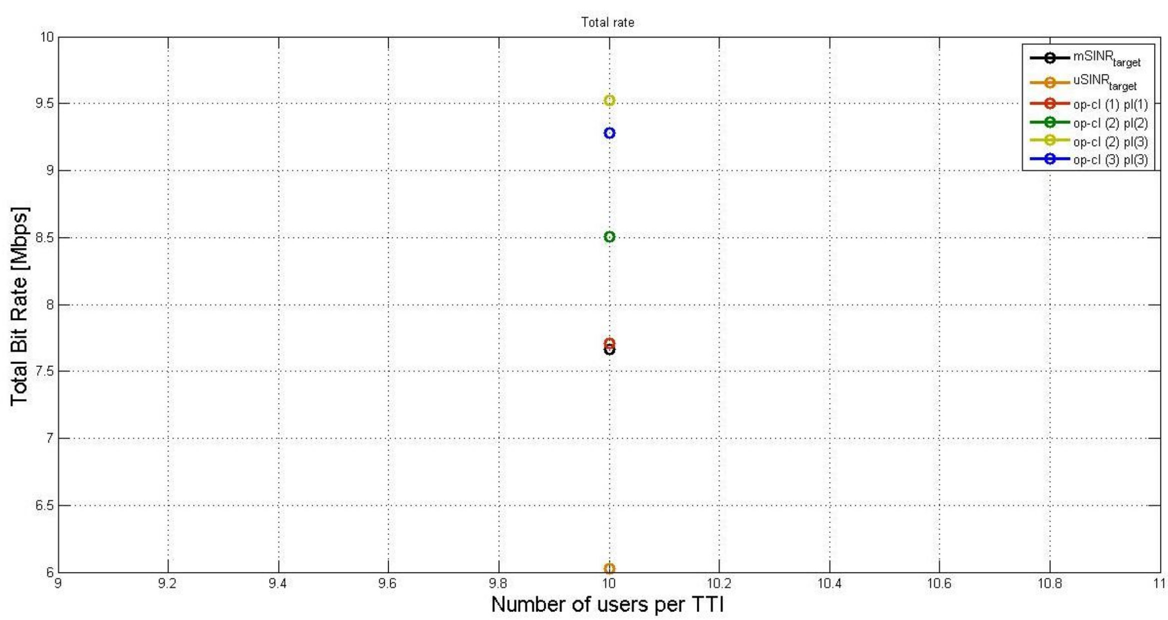


Fig. 4.10 Rate per user and the average achieved total bit rate for op-cl HPC.

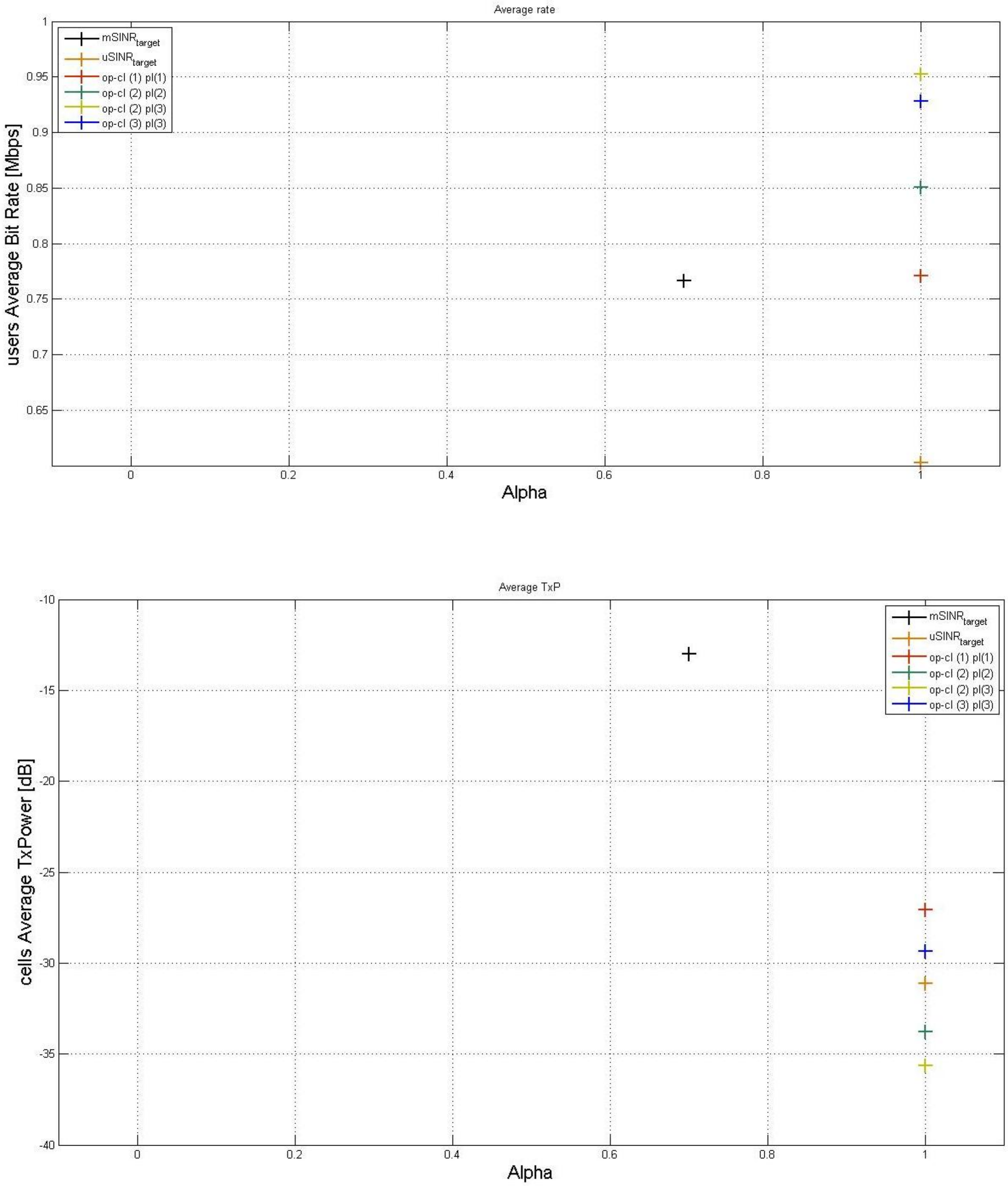


Fig. 4.11 Average transmission power used in the cell, and the average rate in the cell.

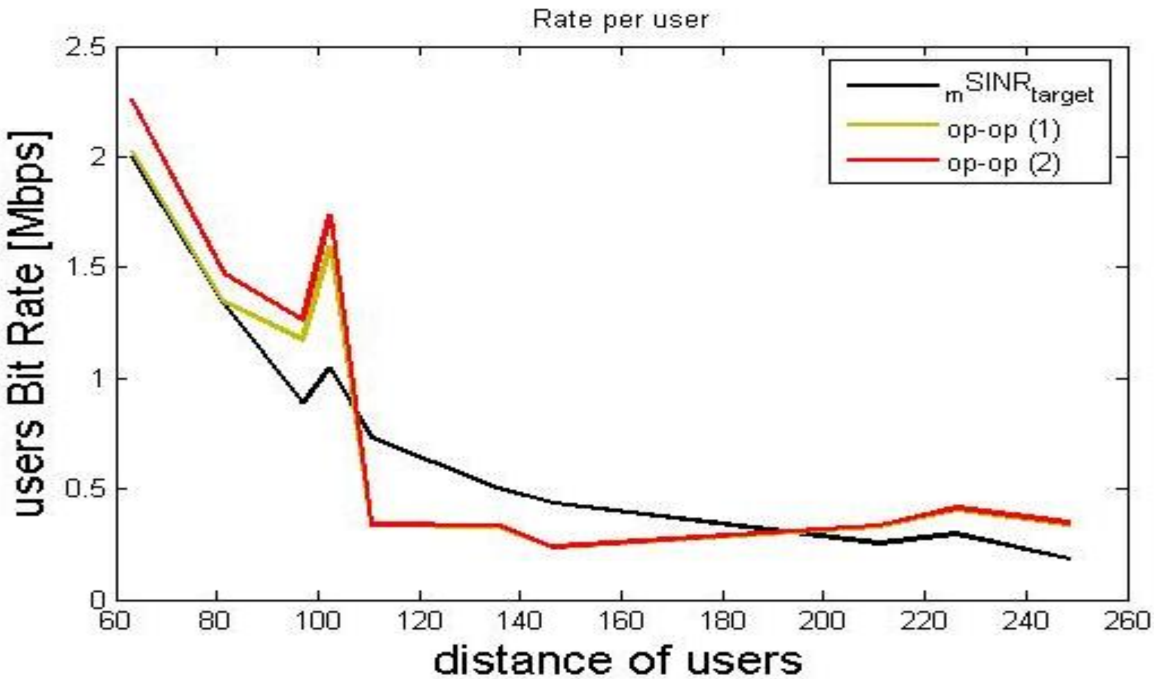
4.2.2 The op-op combination

In general, the op-op combination does not require a lot of signaling, since CE users use OLPC. The problem of using OLPC with the CE users is that they become very sensitive to the variations in the channel conditions, since the main idea of the HPC is using a low power and $SINR_{target}$ for CE users. Furthermore, trying to increase the rate for CC users will mean a decrease in the, already low, rate of CE users because now the CLPC mechanism is absent. The advantage of using the op-op is the reduced signaling but in general CE group has a low performance.

So, even though the performance of the op-op HPC is still better than that of $mSINR_{target}$ (the non-splitting case) the CE users are quite vulnerable in this technique. The performance of the op-op is illustrated in Figs. 4.12, 4.13.

4.2.3 The cl-cl combination

In the cl-cl combination, the CLPC is used for both groups, i.e. CE and CC. The main issue is that CC users in general have enough power and favorable conditions, because of their proximity to the eNB, and they would not need CLPC with its additional signaling, which constitutes the main disadvantage of CLPC. Performance of cl-cl is illustrated in Figs. 4.14, 4.15.



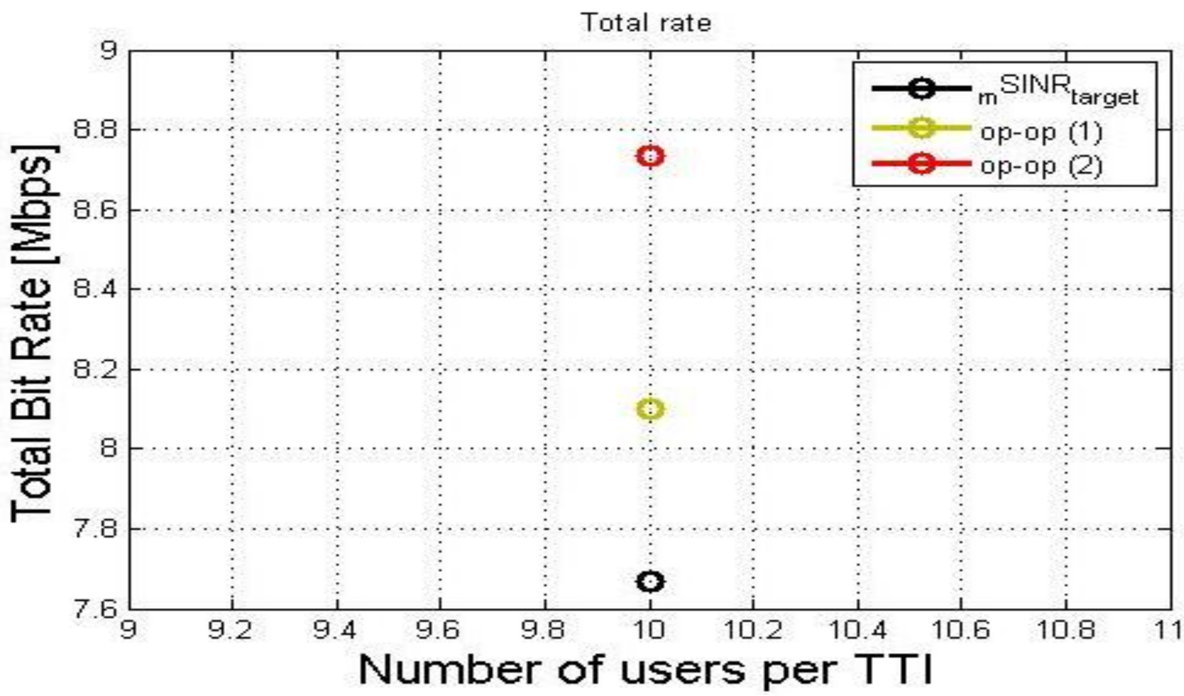


Fig. 4.12 Rate per user and the average achieved total bit rate for op-op HPC.

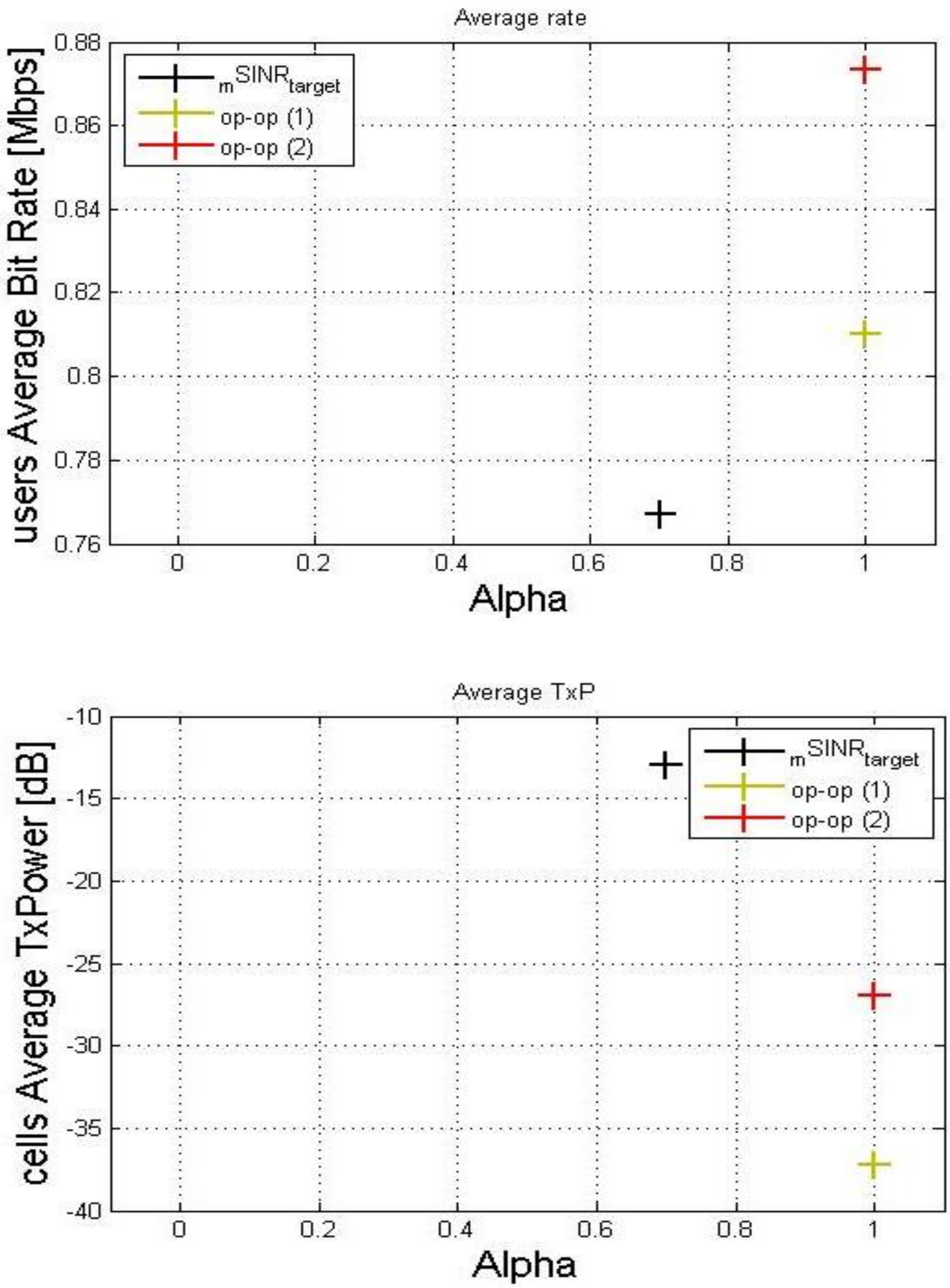
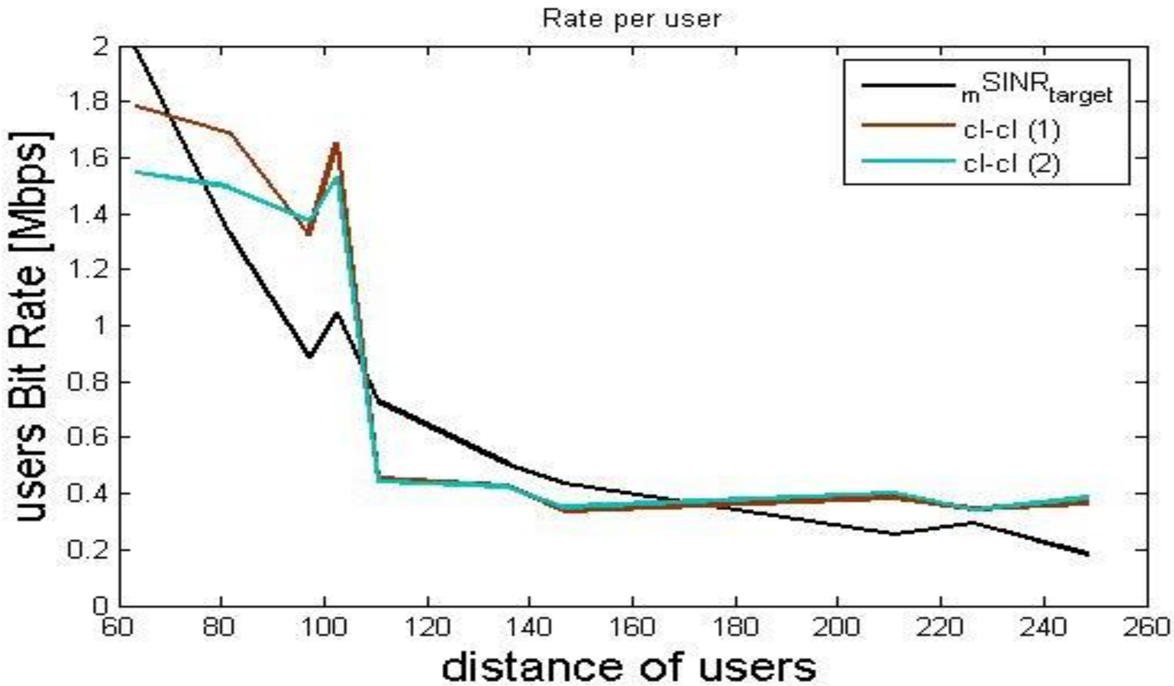


Fig. 4.13 Average transmission power used in the cell, and the average rate in the cell.



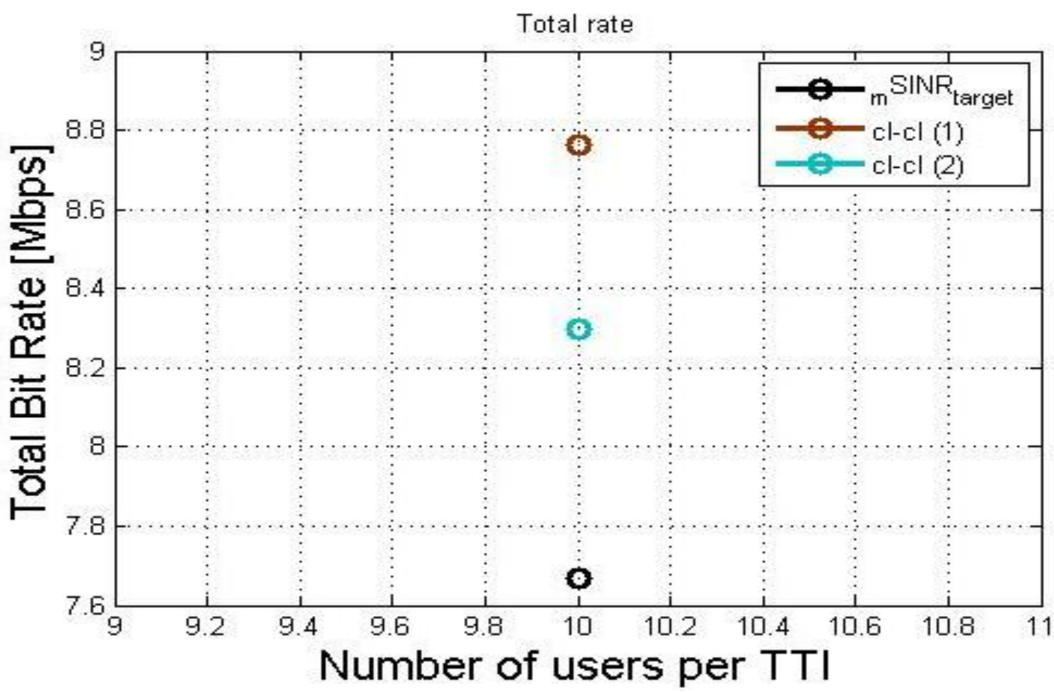


Fig. 4.14 Rate per user and the average achieved total bit rate for cl-cl HPC.

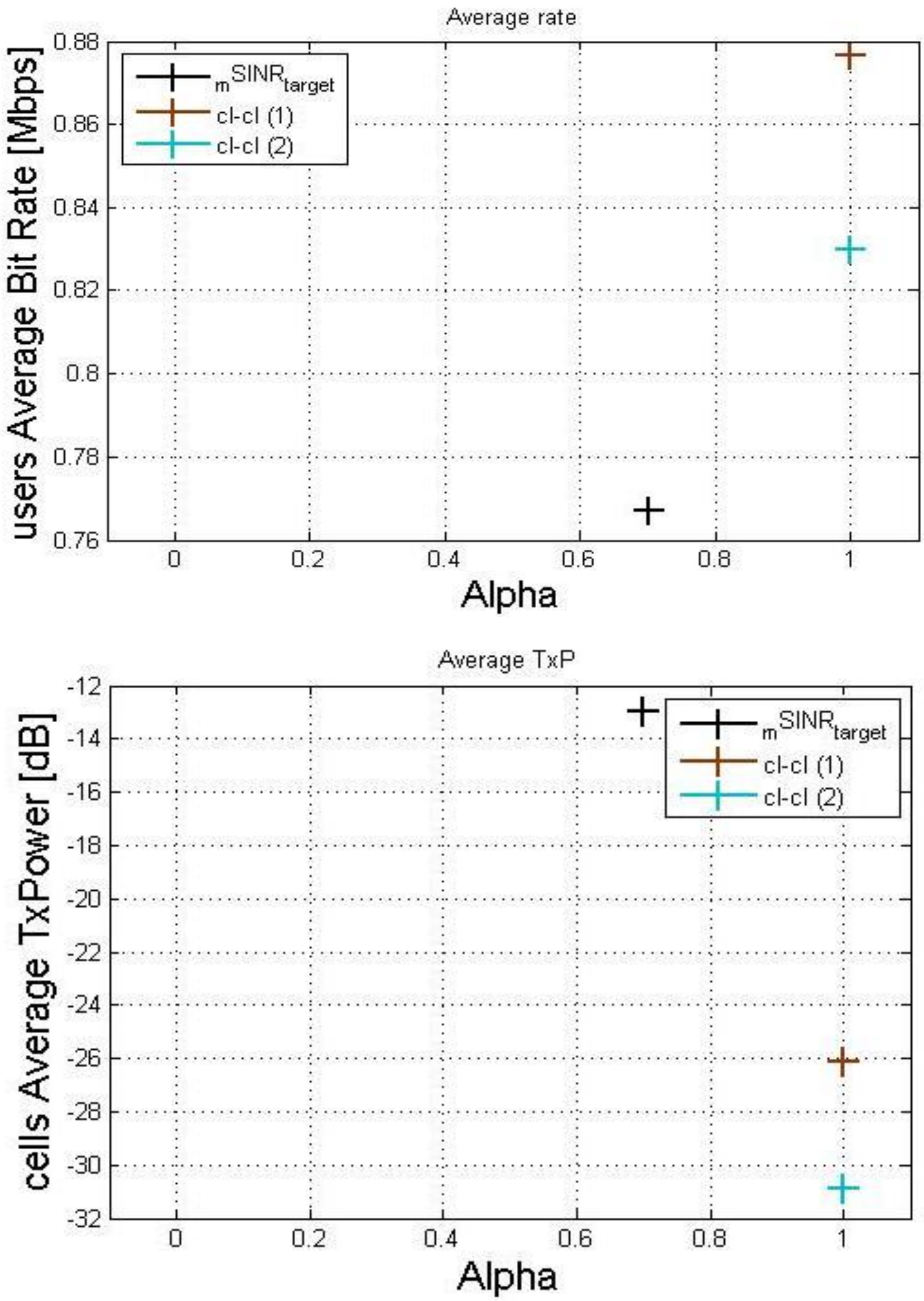


Fig. 4.15 Average transmission power used in the cell, and the average rate in the cell.

4.3 Selection of the best splitting pathloss

In this Section, the choice of the PLS will be investigated. By observing Fig. 4.2, it is noticed that users performance become different at a value around PL = 105. By means of a further inspection of the figure and repeating the simulation for different scenarios, we made an exhaustive search of the best PLS in the range [104: 109] dB. Choosing the smaller value, 104 or less, leads to less interference, since CE group uses less power, but does not allow the exploitation of the full potential of CC users. The opposite is true when the highest value, 109 is chosen as splitting value between CE and CC groups. In this Section some representative PLS are chosen and compared to the non-splitting case in order to show the advantage of a correct choice of the splitting pathloss. The achieved rate for the no-splitting case, non HPC, is 7.6698[Mbps] and the average consumed power to achieve this rate is -13.0030[dBW].

For the sake of comparison, the $mSINR_{target}$, the maximum cell rate without HPC and the $uSINR_{target}$, highest achievable uniform performance, are plotted in Fig. 4.16.

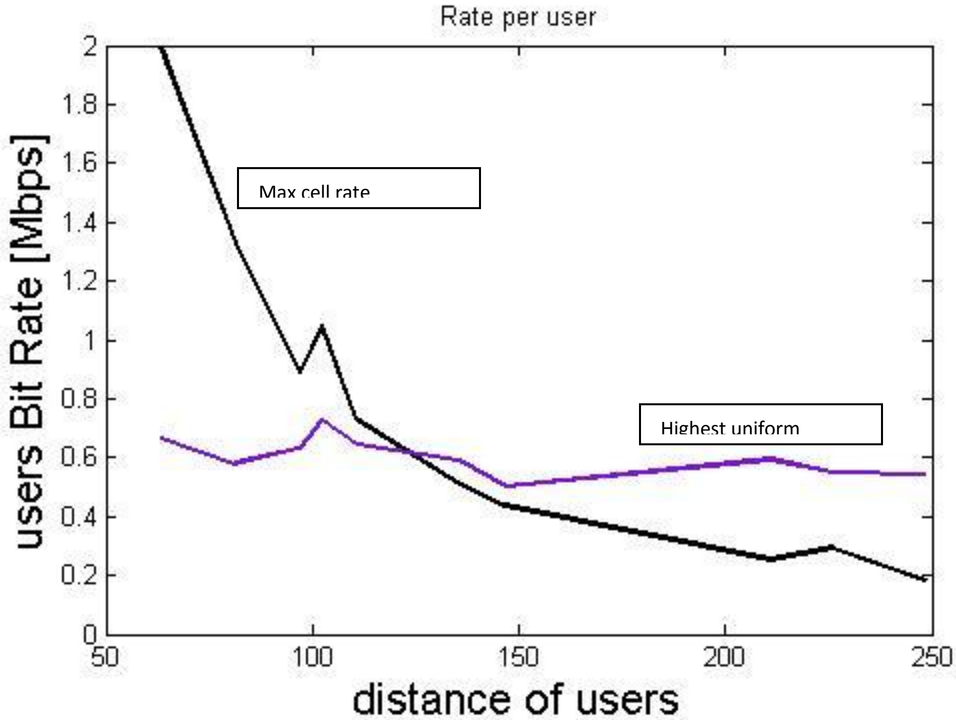


Fig. 4.16 Max cell rate without HPC and the highest achievable uniform performance.

In Table 4.1, a comparison between different PLS is reported, in terms of maximum achievable rate. In the table each result is reported and, between brackets, the difference between this case and the case with no cell splitting is also reported.

PLS	Total rate (difference with non-splitting)	Avg. power(difference with non-splitting)
104.8	10.36 (2.69)	-23.40(10.40)
104	9.76(2.09)	-26.28(13.28)
106	9.46(1.79)	-18.77(5.77)
105	9.16(1.49)	-20.44(7.44)
103	8.97(1.30)	-30.98(17.97)
107	8.92 (1.25)	-22.87 (9.86)
109	8.70 (1.03)	-21.96 (8.95)
108	8.51 (0.84)	-22.40 (9.39)
110	7.99 (0.32)	-21.96 (8.95)

Table 4.1 Max rate for different PLS.

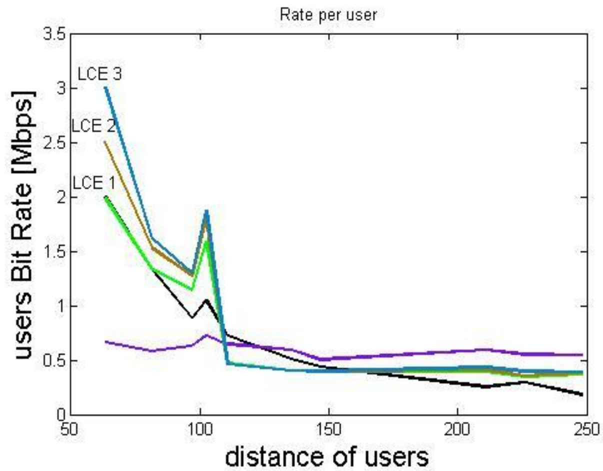
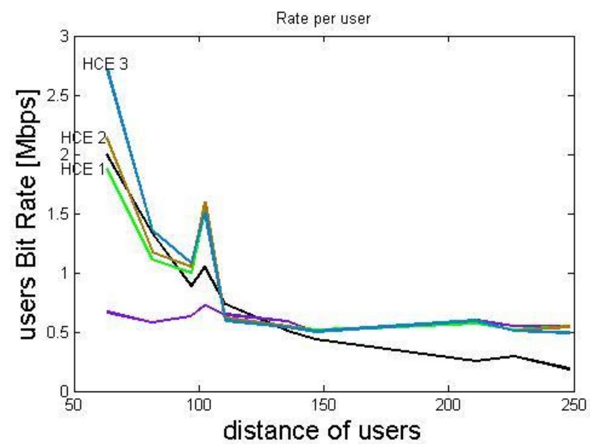
PLS	Target	Total rate	Avg. power	Users' performance
104.8	LCE 1	8.44(0.77)	-39.60(26.60)	
	LCE 2	9.49(1.82)	-35.70(22.69)	
	LCE 3	10.27(2.60)	-28.27(15.27)	
	LCE 4	10.36(2.69)	-23.40(10.40)	
	HCE 1	8.80(1.13)	-31.58(18.58)	
	HCE 2	9.27(1.6)	-29.37(16.37)	
	HCE 3	9.89(2.22)	-22.91(9.90)	

Table 4.2 Performance at PLS=104.8, targeting different SINR values for CE users, in comparison with non-splitting case.

The performance and the chosen $SINR_{target}$ of CE users affect the whole system. Several cases for low CE users $SINR_{target}$ (LCE) and high CE users $SINR_{target}$ (HCE) are reported in Table 4.2. The testing was carried out at PLS equal to 104.8 since it was found to be the best splitting point in terms of overall rate.

It is to be noted as a general rule: the lower the target CE level, the lower the average transmission power, and interference power. This leads to increase in the average cell's rate and CC users' rate.

4.4 Energy efficiency

This section is dedicated to the study of the spectral efficiency (SF) and energy efficiency (EF) of the HPC using PLS = 104.8 for the op-cl combination, with two groups per cell, i.e. CC and CE. The simulation was carried out for more than 2400 combinations, OLPC, CLPC, and values of α. The resulting throughput and the used transmission power were stored, in order to be used for spectral efficiency and energy efficiency computations.

The spectral efficiency was calculated by dividing the rate [bit/second] over the Bandwidth [Hz]. The energy efficiency was calculated by dividing the rate [bit/s] over the used transmission power [W]. Then the spectral efficiency [bit/s/Hz] was sorted in ascending order and the corresponding energy efficiency [bit/joule] was plotted as in Fig. 4.17.

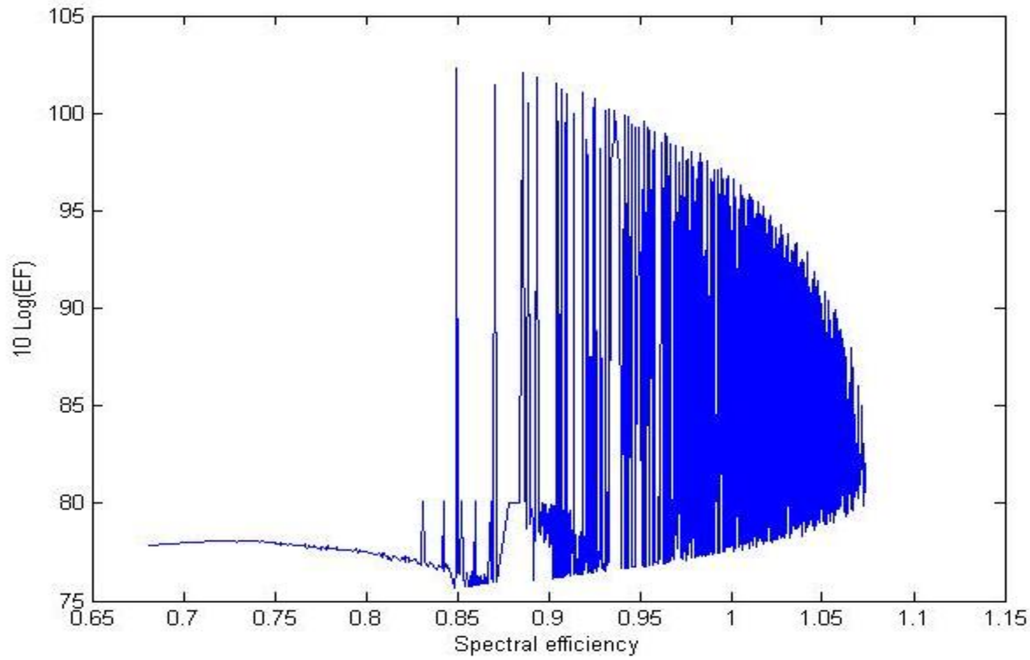


Fig. 4.17 Spectral efficiency and energy efficiency- EF [bit/s/W].

From Fig. 4.17, it can be seen that there is a range of values with a quasi-constant level of EF. At high SF there exist EF peaks instead. As the SF increases these peaks tend to decay. The highest peak corresponds to a CE rate level equal to zero. As the SF increases, the peaks become lower, and the CE rates become higher.

Since one of the goals of this thesis is to find a reasonable performance tradeoff for CE users, the same graph was plotted but for just three reasonably good CE levels. Since the best achievable performance for CE users, in the presence of CC users, is their performance at $uSINR_{target}$; the EF was plotted against the SF when the CE users use $SINR_{target}$ that achieves the $uSINR_{target}$'s performance, and this is the first of the three tested levels – reported as HPC $uSINR_{target}$ level in Fig. 4.18. The second level uses a SINRtarget less by 1 dB than that of the first level, which will lead to some reduction in the CE users' performance, by doing so the interference power is reduced, the transmitted power is also reduced, and both the CC users' performance and the average cell's rate are increased, as noticed from Sect. 4.3. The third level is 2 dB less than the first, which means more CE decrease, and more CC increase.

The results can be observed in Fig. 4.18 Where the HPC in the three cases was compared to the non-splitting case with $mSINR_{target}$. It can be seen that HPC performance is better in terms of energy efficiency and spectral efficiency.

Also, it can be seen that, as the CE SINR level decreases, the achieved SF and EF becomes higher. The reason is that decreasing the SINR target means lower transmission power and lower interference.

The final conclusion is that at high SINR levels for CE users the result is low EF and SF. At very low, very close to zero or zero, CE levels the result is high, the highest in case of zero CE level, EF and high SF. The highest SF for the system is achieved at somehow low CE level.

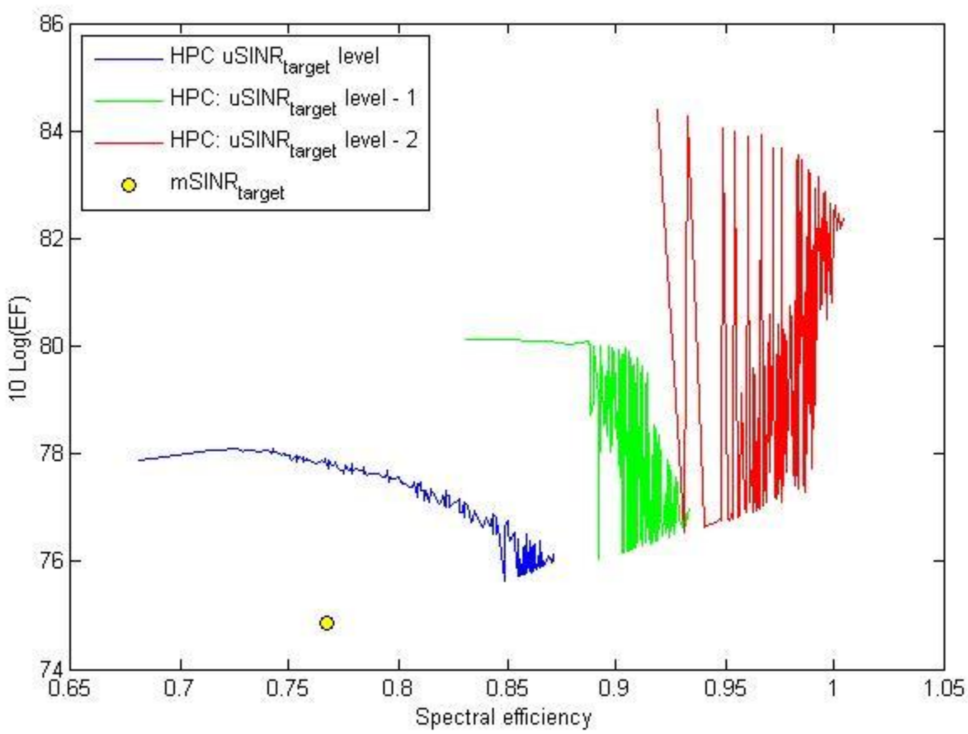


Fig. 4.18 Spectral efficiency and energy efficiency for a guaranteed CE rate- EF [bit/s/W].

4.5 Outage probability

The outage probability was calculated for the system before and after using HPC. It is worth reminding that the scheduler is a round robin (RR) with MCQI. With MCQI even if only one of the user's RBs will not be scheduled, due to bad channel conditions, the user will not be scheduled at all, since the user is assigned the MCS according to the worst RB. Using RR, if a user is not scheduled in a given TTI, it will be scheduled in the next one, if the channel condition on the RBs is adequate. The average number of outage users per TTI in the central cell is reported in Table 4.3 for some of the interesting cases.

Case	Outage	Rate [Mbps]	Tx-Power [dBW]
Max rate (no splitting)	3.7076	7.66	-13
HPC-1	3.6029	10.27	-28.27
HPC-2	3.0830	9.89	-22.91

Table 4.3 Resulting outage, achieved rate, and used transmission power for two HPC examples.

Chapter 5

Analytical formulation

This part of the thesis is dedicated to the verification of the simulation results on the HPC using mathematical formulations and algorithms.

5.1 The SINR feasibility check

In [18] a method was used to check the feasibility of a minimum target SINR for each user.

For a system with a given number of links, a link (i) exists between TX_i and RX_i. A channel gain G_{ij} is defined between TX_i and RX_j. PT_i is the transmission power of TX_i over the link (i) and n_i is the receiver noise at RX_i on link (i). The received SINR of link (i) is

$$SINR_i = \frac{G_{ii}PT_i}{\sum_{i\neq j} G_{ji}PT_j + n_i} \tag{5.1}$$

and an interference link strength (ILS) matrix is defined as

$$ILS_{ij} = \begin{cases} 0, & i = j \\ \frac{SINR_{i,min}G_{ji}}{G_{ii}}, & i \neq j \end{cases} \tag{5.2}$$

Where $SINR_{i,min}$ is the minimum desired SINR for user (i). According to [19], if the maximum eigenvalue of ILS is larger than 1, then this SINR is not feasible. In the case of SINR feasibility, the existence of a feasible power vector must be confirmed. By rearranging (5.1) the power vector (5.3) and the user's link vector (5.4) can be written as follows:

$$\check{P} = (I - ILS)^{-1}\check{u} \qquad (5.3)$$

Where the user's link vector is composed of elements

$$u_i = \frac{SINR_{i,min}\, n_i}{G_{ii}} \qquad (5.4)$$

After calculating the power vector using (5.3), it must be confirmed that the power for each UE is not greater than the maximum allowed power for the UE.

The method is employed to test the used system, described in Table 3.1, in order to find the feasible SINRs. There are 16 CQI-MCS pairs, as already mentioned in Chapt. 1, and hence 16 SINR values were tested in order to find the maximum and minimum achievable SINR in the system among these 16 values.

The mathematical analysis is applied to the channel matrix after taking the average over all the time instants: so only the large scale components, i.e. shadowing and pathloss, are present [20] since the power control mainly operates on medium long term SNR variations, while the scheduling techniques are mainly responsible for the fast ones.

The tested SINR, in linear units, are given in the Table 5.1.

1	0	**9**	5.0699
2	0.2371	**10**	7.8524
3	0.3673	**11**	12.1619
4	0.5689	**12**	18.8365
5	0.8810	**13**	29.1743
6	1.3646	**14**	45.1856
7	2.1135	**15**	69.9842
8	3.2734	**16**	108.3927

Table 5.1 Tested SINR values.

After testing the system, the result was 3.2734, which means that, under the assumption that all the users have the same target SINR, the system is unable to achieve SINRs higher than 3.2734. This value can be interpreted as the $uSINR_{target}$ used in Chapt. 4.

5.2 Cell splitting

The cell is divided here into two groups, i.e. CC and CE, in order to verify that splitting the cell and giving each cell group its own suitable SINR can produce a higher rate.

As in Chapt. 4, the first thing is to find the best splitting pathloss (PLS) point, denoted here as the critical pathloss (PLC), which divides the cell into the two groups. A wide range of PLC was tested and, for each PLC, all the possible 16 SINRs were tested in each group. The PLC that achieves the maximum rate was found to be PLC = 104.8. It is worth noting that here PLC comprises pathloss and shadowing and this notation is used for simplicity. There are, in particular, two interesting SINR pairs at PLC = 104.8, shown in Table 5.2:

CC	CE
45.1856	3.2734
108.3927	2.1135

Table 5.2 SINR values at PLC 104.8

From the results, it can be seen that the main idea of HPC is confirmed. Splitting the cell while keeping the CE at a lower value, allows the CC performance to be increased.Some important remarks:

1. It is found that even cancelling CC totally, CE cannot increase achievable SINR over 3.2734, which confirms what reported in Chapt. 4, i.e. that CE users are mainly limited by other CE users.
2. Having SINR for CE = 3.2734 is not a disadvantage in HPC, because this was the $uSINR_{target}$ of the whole cell, as mentioned in the previous section.
3. A difference between this mathematical analysis and the simulation carried out in Chapt. 4 is that, in this test, all users within each group must target the same SINR, e.g. all CC users 45.1856 and all CE users 3.2734, while in the simulation, there is more freedom in the OLPC and CLPC parameters.

5.3 Additional cell splitting

As already observed in Chapt. 4, the cell can be divided into more groups. One of the limitations of the simulation approach is the simulation time which allowed the test of just two groups, i.e. CC and CE. In the mathematical analysis further cell splitting can be investigated.

At the beginning of the procedure, there is one group in the cell, i.e. no splitting, with maximum feasible SINR target = 3.2734. After that, the cell is divided into two groups: CC and CE, with CE keeping the SINR target = 3.2734 and CC the SINR target = 45.1856. The next step is to divide each of these two big groups into two more groups, while trying to keep the CE SINR target as high as possible. It has to be noted that one of the main targets of this thesis is to keep a reasonable performance for CE users, since they already have low rate. Some of the main result of the division can be seen in Table 5.3.

CC1	CC2	CE1	CE2
45.1856	108.3927	3.2734	3.2734
108.3927	108.3927	5.0699	2.1135
108.3927	108.3927	12.1619	1.3646

Table 5.3 SINR values of the cell groups.

Starting from the first row it can be seen that CC2 performance was, in the case of only two groups, passed by CC1 performance and by splitting CC into two groups (CC1 and CC2) CC2 can reach its full potential. Considering the second row, it can be seen that shifting down of one level in the SINR target for CE2, the interference due to CE2 will be reduced and hence CE1 and CC1 can increase their performance (this also implies that most of CE2 users affect both CC1 and CE1, but not CC2). By reducing CE2 furthermore, CE1 can have more advantage, as seen in the fourth row.

The conclusion from the SINR feasibility point of view is that by splitting the cell, the system was able to have 108.3927 for CC and 2.1135 for CE instead of 3.2734 for the whole cell. By further splitting CE1 can have 5.0699 and CE2 can have 2.1135, instead of 2.1135 for the whole CE area. Furthermore, it was confirmed that targeting high SINR for CE is not feasible; this will translate in real implementation as increase in the transmission power without achieving any rate gain, in other words power waste with interference increase and no rate increase.

5.4 Cell splitting for random users' location

In Sect. 5.2, PLC was found through the mathematical analysis for certain users locations. Here we show the results for one thousand of random extractions of the users locations. This histogram of the resulting PLC, in Fig. 5.1, indicates a general splitting point, regardless of the knowledge of the users' locations.

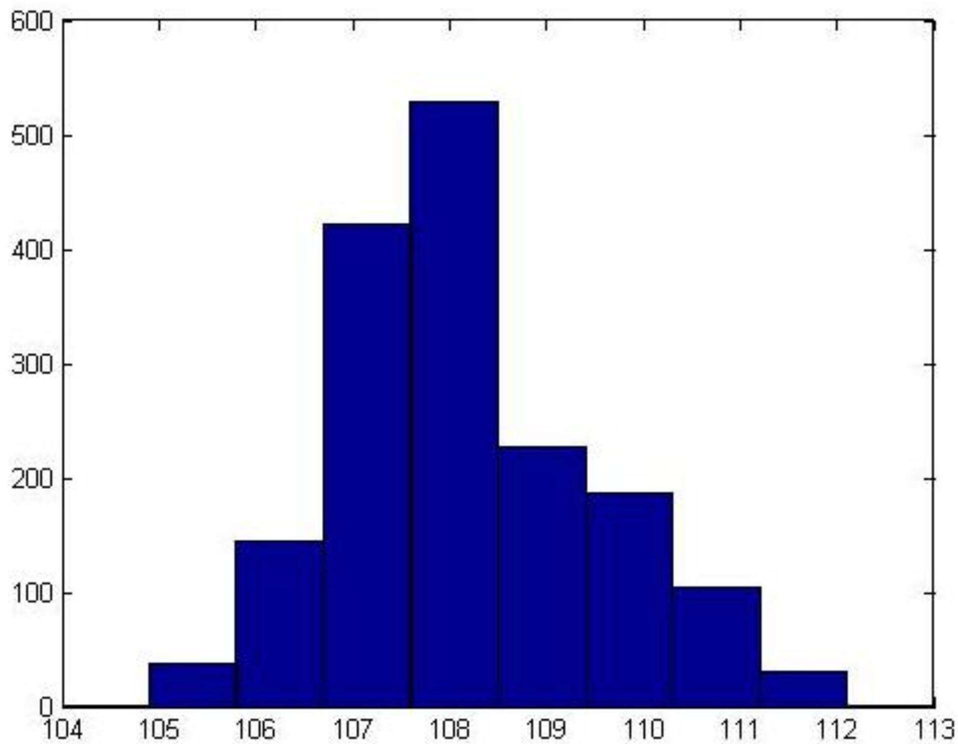


Fig. 5.1 Histogram for general PLC.

5.5 Comparison with the simulation results

In Sect. 5.2, we have showed that using different SINR target for two cell parts improves the overall spectral and energy efficiencies. It was also proven that CE users are mainly limited by other CE users in the adjacent cells. These results confirm the results obtained from the simulations. In this section the PLC obtained from the simulations is compared to the PLC obtained from the analytical procedure described in this chapter.

It is worth reminding that there are some differences between the operations in the mathematical analysis (MA) method and in the simulations (SM). The first is that the MA method searches for the best uniform performance for CE and CC, while SM searches for the best one regardless of the uniformity constraint. The second difference is that in MA the channel average was taken before calculations, while in the SM method the channel matrix was used as it is with its entire components (so the fast fading is still present).

The results of the MA search for PLC within the main central cell were [104.8, 105, 105.2, and 105.4]. In Sect. 5.2 PLC = 104.8 was selected for numerical testing. Some remarks are:

1. There is no difference in the number of users in the CC and CE in all the cells between the cases [105, 105.2, and 105.4]. So we consider them equivalent from a performance point of view and these three values will be represented hereafter by 105.
2. There is no relevant difference in the number of users in the CC and CE within the main cell between 104 and 105.

It is to be noted that the MA imposes that all the users within each cell group must be able to achieve the same SINR. On the other hand, in SM variance between users' performance is allowed. In order to have a meaningful comparison between the MA and SM, the SM was repeated, Fig. 5.2, while searching for the maximum uniform behavior.

It can be seen from Fig. 5.2, that 104.8 is equal to 105, both of them are higher than 106, this concedes with the MA results. In the figure the maximum uniform for each case is reported, e.g. pl105, and the first non-uniform is also reported, e.g. pl106non.

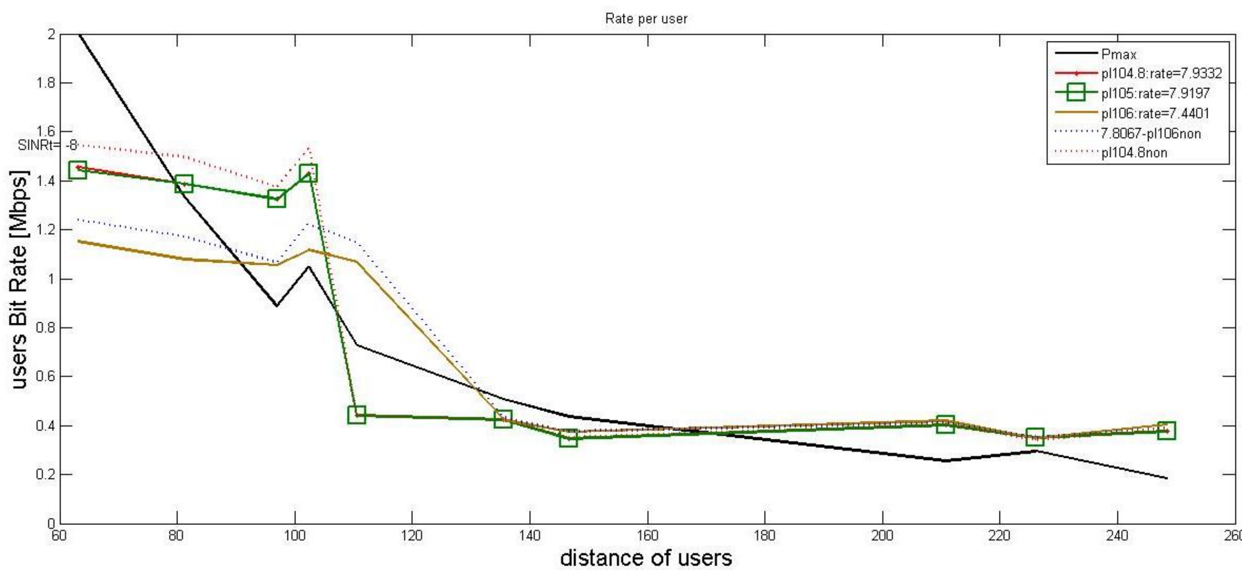


Fig. 5.2 PLC search for maximum uniform performance.

Conclusions

Power control is used to set the transmitted power in order to achieve or maintain a desired data rate in the terminals. However, setting the transmitted power is not arbitrary since using too much transmission power clearly leads to high inter-cell interference and using too small transmission power leads to low throughput. Hence, a suitable transmission power value should be set according to a number of trade-offs and optimization issues.

LTE uplink uses an orthogonal scheme, SC-FDMA, which allows multiplexing of different users within the same cell without having problems such as near far effect or intra-cell interference. Regardless the orthogonality of SC-FDMA, which limits intra-cell interference, there is still the problem of inter-cell interference as, in general, LTE uses a frequency reuse 1 and high interference levels from other cells UEs limit the uplink coverage if the interfering powers are not controlled.

Power control is also used to improve the energy efficiency and this is important for the entire system but, in particular, for portable devices, which have a limited amount of available energy and instantaneous power. Furthermore, currently the research is shifting toward the use of sustainable energy sources, in which energy savings play a major role w.r.t. the traditional sources.

In a few words, power control has a primary role in the determination of system capacity, coverage, user quality, and power consumption.

LTE uses a combination of open loop (OLPC) and closed loop power control (CLPC). While open loop is based on pathloss estimation, closed loop is a faster adaptation used to control interference and tune the power setting in order to react to the channel and traffic conditions.

In this thesis, an introduction to the power control in LTE has been given, together with a comprehensive analysis for both close loop and open loop power control.

However there are some limitations in the conventional power control techniques; having a high cell rate at the expense of the cell edge users' performance, or having a moderate cell edge users performance at the expense of average cell rate performance. In order to overcome this problem, some modifications have been done to the conventional power control techniques and the idea of Hybrid power control (HPC) comes from this necessity. Using HPC allows an improvement in cell edge users' rate, a major reduction in the power consumption and an improvement in the average cell rate.

The basic idea of HPC is that users within the cell are divided into two or more groups; each group is decided according to pathloss w.r.t serving eNB and each group has a different target Signal-to-Interference and Noise Ratio ($SINR_{target}$) and a different maximum achievable rate. If the system is divided into two groups we can define a cell edge (CE) users group, and a cell center (CC) users group. It can be shown that CE users have a rate limit: trying to achieve a higher rate by using more power (or equivalently $SINR_{target}$) will lead to a power loss and an increase of interference without any additional gain. It is also worth noting that this rate limit is independent of the maximum allowed power for the UE (an unlimited power would not change the result) since it is determined by interference.

HPC was tested for a SISO system with 7 cells. The attained performance was better than that of the conventional power control techniques in terms of achieved rate for all the users, including cell edge users, and in terms of power consumption. HPC can achieve an improvement in the average cell rate around 23%. Moreover, the average transmitted power is reduced by more than 22 dB.

The outage probability and energy efficiency for the HPC were also tested. It has been shown that the HPC is characterized by high energy efficiency. The HPC performance was tested through simulation and mathematical analysis, confirming that it is possible to derive some fundamental design parameters from analytical procedures.

For future research work, the next logical step will be the extension of HPC to a more complicated and advanced system, e.g. using the HPC in a system with more cells, and using it in the context of MIMO technology. Mainly the next research areas are related to study the HPC with other technologies and techniques in order to understand and manage the impact of interference as much as possible and taking into account severe energy savings constraints. This is also one of the major themes of the next generation mobile systems (5G). The following list constitutes the backbone of future research steps.

- Analysis of HPC in multi-tier environments. HPC usually achieves very good performance when the CLPC is used for CE users; adding another tier of cells will add interference sources to the 1st tier of cells and the CLPC will have to respond to these changes by changing power, which will affect the behavior of the CLPC of the main cell. This complicates the analysis of the overall scenario.
- HPC with MIMO. Using MIMO could introduce intra-cell interference and more complicated relations and trade-offs in the radio resources management.
- HPC in cognitive radio. Also in this new context, HPC should be analyzed and adapted according to the constraints of secondary users w.r.t. primary users [22].
- Currently HPC uses OLPC, and CLPC. Studying the behavior of other techniques, such as the interference based power control (IBPC) [23], should be necessary.
- Combining HPC with more sophisticated scheduling techniques, including schemes for inter-cell coordination.

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