Study of techniques for increasing reliability and throughput in wireless fading networks

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Περίληψη

Η ενδοκυψελική παρεμβολή αποτελεί ένα σημαντικό πρόβλημα στα ετερογενή κυψελοειδή δίκτυα (ΕΚΔ). Σε αυτό το άρθρο προτείνουμε μία λύση η οποία βελτιστοποιεί την απόδοση των ΕΚΔ δεδομένης της ενδοκυψελικής παρεμβολής με την χρήση δεκτών οι οποίοι ακυρώνουν την παρεμβολή και είναι υλοποιημένοι στη μεριά των χρηστών. Έπειτα, προτείνουμε ένα πλαίσιο βελτιστοποίησης το οποίο αποσυνδέει αυτές τις λειτουργίες στους macro και pico σταθμούς βάσης. Μπλοκ πόρων κατανέμονται στους χρήστες με τέτοιον τρόπο ώστε η τεχνική SIC να βελτιστοποιείται. Το κύριο αποτέλεσμα είναι η τεχνική SIC να βελτιστοποιείται τοπικά χωρίς την χρήση κάποιου κεντρικού ελεγκτή αξιοποιώντας την ποικιλομορφία του καναλιού καθώς και την ύπαρξη πολλών χρηστών. Επίσης, αναλύεται η ανάπτυξη τεχνικών μετάδοσης δεδομένων για αύξηση του ρυθμού μετάδοσης και της αξιοπιστίας ενώ αξιολογείται η εφαρμογή τους σε ένα ασύρματο περιβάλλον με διαλείψεις.

ABSTRACT

Intra-cell interference is a major problem that is present in heterogeneous cellular networks (HCNs). In this paper we propose an optimization framework for improving the performance of HCNs in the presence of intra-cell interference when interference cancelling receivers are deployed at the users. Next we propose an optimization approach that decouples the operations at the macro and pico BSs. Resource blocks are allocated to the users in such a way that SIC is optimized at the UEs. Our main result is that SIC can be optimized locally without a centralized controller if we exploit the diversity of the channel across the RBs and the existence of multiple users. Further analysis of transmission modes in a wireless fading network is taking place in order to study it's performance under random channel conditions.

1.

1.1 Introduction

To keep up with the need for higher data rates in wireless cellular networks there are few options at the disposal of the mobile operators. One of the most promising ones is the deployment of heterogeneous networks (HetNets). The main reason that HetNets have such potential is that they achieve higher spatial reuse through the deployment of low power base stations (BS) like pico BS (PBS) and femto BS (FBS), that form around them picocells and femtocells respectively.

One of the key problems unique to HetNets is that of *intra-cell* or *cross-tier* interference. Intra-cell interference is caused between the macro BS (MBS) and the low power BSs. Fig. 1.1 illustrates this case where the MBS interferes with the PBS at the picocell user 1. One strategy for handling this type of interference in HetNets, is time-domain resource partitioning where the macrocells shut off their transmissions for a subset of the available resources [1]. This technique was recently standardized through the introduction of almost blank subframes (ABS) in 3GPP LTE under the more general scheme of enhanced intra-cell interference coordination (eICIC). Users associated to the picocells can achieve higher data rates in these ABSs since interference from the MBS is limited to the bare minimum [2]. Nevertheless, resources must still be allocated to the macrocell to ensure umbrella coverage for the complete network. Andrews et al. reported in [1] that for deployments in the order of less than 10 small cells and less than 100 users, the optimal fraction of ABSs is approximately 50%. But even with resource blanking, during the MBS transmissions in the regular subframes (RS), the small cells have to suffer from inferior performance.[1] Consequently, it is necessary the small cells should adopt mechanisms that combat the high power interference from the MBS.

One way to deal with this problem is apply multi-user detection (MUD). In [4] the problem was studied and the proposed solution involved a type of sectorization inside the macrocell so that interference is controlled more efficiently between the small cells and the macro cell. In that work the author assumed that it is possible that a transmitter, like a PBS or FBS, may not transmit in a specific time of frequency resource. This is typically undesired in distributed HetNets since it may only happen in the case of under-loaded small cells. How-

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[1] As it was observed in [3] due to this phenomenon *"the average PHY data rate from a pico in a non-ABS subframe is very small in many instances due to very high interference from the macrocell"*.

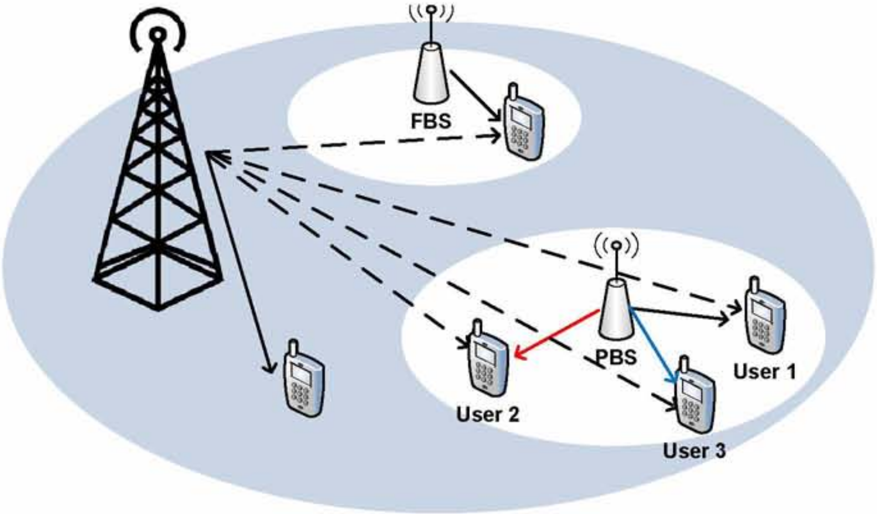

Fig. 1.1: Illustrating intra-cell interference in a HetNet. Solid lines indicate the intended source-destination pair. Dashed lines indicate intra-cell interference during the resources that are shared by the MBS and the PBSs.

ever, there is potential room for further improvements if the MBS and small cells coordinate. In HetNets the problem of optimal power allocation for receivers that employ SIC was studied in [5]. The authors assumed that the MBS and the PBSs coordinate in order to decide the power of each individual transmission so that SIC is optimized at each receiver. Nevertheless the formulated problem was targeting the minimization of inter-cell interference, which is not the primary concern for a HetNet while frequency-domain ICIC techniques can be used [2]. It is also clear that this approach sets very stringent requirements for the backhaul communication since the MBSs across several macrocells have to coordinate. Furthermore, from an optimization point of view this is clearly a very difficult NP-hard problem that is solved with a heuristic while an optimal solution cannot be provided. Less coordination has also been investigated for optimizing IC in HetNets. Sahin et al. [6] considered IC at the users by designing a special message structure at the MBS that it enables the decoding at the user when the picocell also transmits. Even though SIC may offer benefits, all the previous schemes follow a passive behaviour in the sense that an event takes place and then actions are taken to recover from it. However, the recent trend is that the small cells are more aware of their environment. Adhikary et al. [7, 8] introduced the term *cognitive femtocell* to describe precisely this behaviour of a PBS that may overhear the transmission of the MBS. The authors allowed the PBSs to decode the MBS control channel so that it could apply different power control strategies. The PBSs either shut off their transmissions or limit the transmit power to a prescribed level. Besides blanking through ABS, MUD, intra-cell interference can also be dealt with other methods that also required coordination like Massive MIMO [9] and CoMP [10]. For example in [10] the authors considered the use of CoMP from both the MBS and several PBSs as a means to minimize interference in specific resource blocks (RBs) and users in an LTE system.

In this paper we investigate the the performance improvement of UEs in HetNets that experience intra-cell interference. We employ optimized SIC and RB allocation. This paper builds upon the fundamental observation that different RBs allocated to a user, that is associated to a PBS, experience different channel fades and the same is true for the RBs allocated to the macrocell users. Hence, when the same RBs are re-used across the MBS and the PBS a user can have different probability of using SIC efficiently at different RBs since SIC is sensitive to the power of the two interfering signals [11]. Consequently, there is strong motivation to allocate RBs to UEs in such a way that the macro interference is efficiently decoded at the users associated to the picocells. The fundamental concept of exploiting channel fades for SIC was proposed for cooperative relay networks in [12]. In that work two interfering signals are received at several relays but the one that is selected for forwarding the signal to the next hop is the one that satisfies a "SIC-optimal" heuristic criterion. In light of this observation we first propose an optimization framework, where channel knowledge is assumed to be available in a central system controller (e.g. the LTE eNB). Next, we consider the case that the PBSs have only local channel knowledge, and they cannot coordinate their decisions with the MBS. As illustrated with our comprehensive performance evaluation, this last variation of our system performs very well.

Finally, we assume that the picocells do not have CSI availability for the channel from the MBS to the target UE. We consider a system where the MBS independently schedules its transmissions to the desired user. The task of the PBS is to allocate to each associated UE an RB in such a way that it enables optimal performance under SIC. We model the performance of the system under opportunistic SIC.

1.2 System Model and Assumptions

Network Model. In Fig. 1.1 we present the network topology that we study in this paper and it includes a single macrocell with a MBS, the PBSs, and the users. Each base station j in the set $\mathcal{J}$ communicates with the set of users $\mathcal{N}_j$. During all the resources all the small cells transmit and interfere with every active user in the network. Thus, we consider *resource reuse* across BSs of the same tier (PBSs in our case) which is one of the main benefits of small cells since it allows spatial reuse. Also, the available time-frequency resources is the set of $\mathcal{K}$ RBs. The aggregate average interference power that a node receives during these regular subframes is denoted as $I_{\mathrm{RS},i}$.

User Model. The users associate to the proper BS by using an SINR

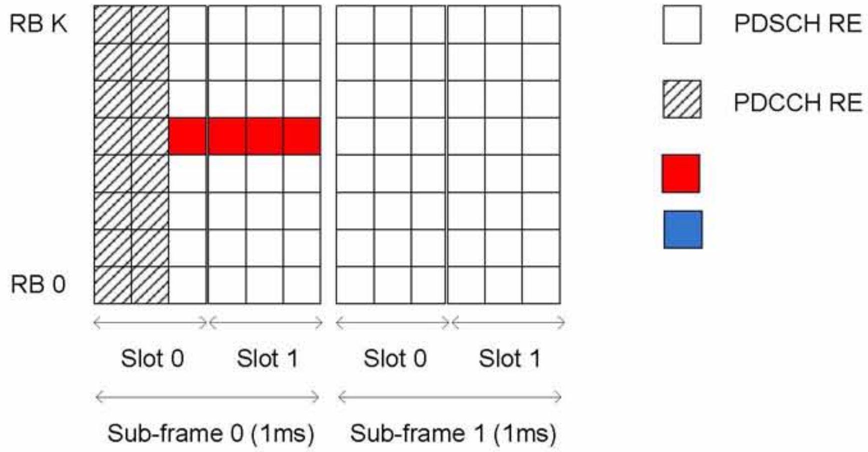

Fig. 1.2: In LTE-A each RB consists of several resource elements (RE) depicted in a horizontal line. These RBs are allocated to the users associated to the MBS. The same RBs are allocated to the "red" and "blue" users. Our objective in this paper to perform efficiently and scalable this allocation.

biasing rule and all the PBSs are assumed to have backlogged data for all the users [13].

Channel Model. Every node has a single omni-directional antenna that can be used in half-duplex mode for transmission and reception. We denote the channel from the j-th BS to the i-th user for the k-th RB as $h_{j,i,k}$. We assume that the fading coefficients are independent and $h_{j,i,r} \sim \mathcal{CN}(0,1)$, $h_{r,i} \sim \mathcal{CN}(0,1)$, i.e. they are complex Gaussian random variables with zero mean and unit variance. All the channels, are considered to be block-fading Rayleigh. The channel coefficients are quasi-stationary, that is they remain constant for the coherence period of the channel that is equal to the transmission length of the complete subframe (Fig. 1.2). Each subframe is divided into two time slots during which we transmit an *information block* of L symbols (Fig. 1.2). We also consider the path loss and shadowing effects according to the LTE channel model [2]. Additive white Gaussian noise (AWGN) is assumed at every receiver with variance σ^2.

LTE and control channels. The LTE PDCCH (Physical downlink Control Channel) is the channel (a group of RBs as illustrated in Fig. 1.2) that carries the control information about the data that will be transmitted in the current subframe (and the uplink information). This means the UEs must decode it successfully if they want received data. A critical aspect of the PDCCH is that it carries a message called DCI (Downlink Control Information) that includes the RB allocations for a UE. In our system the DCI of the PDCCH of the MBS is also assumed to be decoded by every PBS.

CQI. We also assume that users provide only *average channel quality* feedback (CQI) to the base stations. The feedback is assumed to be received every 10ms which is a again the typical case for LTE-A systems [2].

Implementation. In our system each BS first estimates the average communication rate C_{ji} between itself an every associated user. The BS measures the average channel gain $\mathbb{E}[|h_{j,i}|^2]$ for this purpose. Note that the average channel gains, or the CQI in the LTE terminology, can also be easily transmitted from each user to the BS since they only correspond to path loss and shadowing. Also, all the users periodically transmit to the BS the average power of the interference ($I_{\mathrm{RS},i}$ and $I_{\mathrm{ABS},i}$) that they receive so that it can be used in all the rate expressions we develop next.[2] It is important to clarify at this point that none of the previous functionality requires any type of modifications to the existing protocol stack of a typical wireless device. This feedback of the CQI and the interference power, is what is typically implemented in practical systems [11].

1.3 Opportunistic Successive Interference Cancelation (OSIC)

Assume that the PBS and the MBS communicate at rates of m and m_{MBS} bits/symbol, respectively. In the first time slot of the regular subframe both the PBS and the MBS transmit their information blocks named x_{MBS} and x_1 simultaneously. Thus, for the first slot the baseband model for the received interfering symbols at user r is $y_r(1) = h_{\mathrm{PBS},r}(1)x_1 + h_{\mathrm{MBS},r}(1)x_{\mathrm{MBS}} + w_r(1)$. The same expression holds for the transmission of the second information block x_2 from the PBS during the second slot. In these expressions w_r is the AWGN sample at the relay. After the end of regular subframe, a relay user attempts to decode the two symbols x_1, x_2 for each slot by employing ordered SIC (OSIC). That is, the symbol with the highest energy/bit is decoded first while the other symbol is treated as noise [11]. If there was no interference the following condition must be true so that block x_1 from PBS is decoded:

$$\log_2\left(1 + \frac{P_{\mathrm{PBS}}|h_{\mathrm{PBS},r}|^2}{\sigma^2}\right) \geq m \Rightarrow \frac{P_{\mathrm{PBS}}|h_{\mathrm{PBS},r}|^2}{\sigma^2(2^m - 1)} \geq 1$$

The fractional term in the RHS of the last derivation is essentially the normalized SNR/bit that is required for decoding m bits/symbol [14]. We can get a similar expression for the MBS data and by assuming $\mathbb{E}[|x_1|^2] = \mathbb{E}[|x_{\mathrm{MBS}}|^2] = 1$, we conclude the following condition must be true so that x_1 is decoded first:

$$\frac{P_{\mathrm{PBS}}|h_{\mathrm{PBS},r}|^2}{2^m - 1} > \frac{P_{\mathrm{MBS}}|h_{\mathrm{MBS},r}|^2}{2^{m_{\mathrm{MBS}}} - 1} \tag{1.1}$$

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[2] LTE Rel. 8 already implements the communication of the power of the local interference though the high interference indicator HII.

In case x_1 is correctly decoded, it is then subtracted from the aggregate signal $y_r(1)$.[3] The same OSIC scheme is applied for $y_r(2)$. Regarding the implementation of the cancellation mechanism it is executed at the level of *information blocks*. The successful decoding of information block x_1 is verified with the use of an error correcting cyclic redundancy check (CRC) code.[4] Thus, upon the successful decoding, and with CQI at the relay (in this example $h_{\text{PBS},r}$), we can completely remove/cancel a complete block from the aggregate received signal $y_r(1)$ allowing the detection of the second block.[5]

1.3.1 Average Data Rate with OSIC

The average data rate for user i associated to PBS j under MCS l is calculated as [14]:

$$C_{jikl} = l \cdot eff \cdot S \cdot (1 - P_s)^{L/l} \text{ bits/sec}, \ \forall l \in \mathcal{M}, \tag{1.2}$$

where S is the symbol rate, eff is the efficiency of the MCS, and the probability of symbol error P_s under 2^l-QAM is [14]:

$$P_s \quad = \quad 4(1 - 2^{l/2})Q\Big(\sqrt{\frac{3}{2^l - 1}\gamma_{jik}}\Big) \tag{1.3}$$

If the signal from the PBS j is stronger, then PUE i in RB k achieves an SINR/symbol equal to:

$$\gamma_{jik}^{\text{PUE1}} = \frac{P_{\text{PBS}}|h_{j,i,k}|^2}{P_{\text{MBS}}|h_{0,i,k}|^2 + I_{\text{PBSs}}(i,k) + N_0} \tag{1.4}$$

And if the signal from the MBS is stronger then

$$\gamma_{jik}^{\text{PUE2}} = \frac{P_{\text{PBS}}|h_{j,i,k}|^2}{I_{\text{PBSs}}(i,k) + N_0} \tag{1.5}$$

For the MBS we have

$$\gamma_{ik}^{\text{MUE}} = \frac{P_{\text{MBS}}|h_{0,i,k}|^2}{I_{\text{PBSs}}(i,k) + N_0} \tag{1.6}$$

In all the above expressions $I_{\text{PBSs}}(i,k)$ is the aggregate interference power that user i receives at RB k.

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[3] It is possible that different rules are used for selecting the symbol to be decoded first or even a completely different IC scheme. Our central concept is to cancel the interference of the MBS and extract the PBS data block.

[4] LTE uses a CRC for multiple resource blocks that is called the transport control block.

[5] Ideally we would like to use as a relay a user that we know it has decoded data. However, due to practical constraints we do not assume that all the users are listening like cooperative diversity protocols do.

1.4 Transmission Modes and Signal Decoding Algorithms

As mentioned above, we propose a method to maximize the total throughput of the cell. To accomplish this, we have three possible transmission mode options which can dynamically be selected according to the Rayleigh channel gain of every available user. In the following section, we describe these techniques more in depth.

1.4.1 Direct Transmission

The DT mode which is enabled in every BS is the default way of transmitting information data in the wireless network. In this mode only one BS is active, so there is no diversity and no cooperation between the BS's. The received signal in user$_\mathrm{k}$ antenna is:

$$y = hs + w,$$

where $h \sim \mathcal{N}(0,1)$ is the Rayleigh gain between the BS and the user, $s \sim (0,1)$ is the transmitted symbol and $w \sim \mathcal{N}(0,N_0)$ is the White Gaussian noise. As h is a Linear time-invariant (LTI), and so not an ideal channel, Inter Symbol Interference (ISI) distortion appears. To expunge this, we need to equalize the symbol using Zero Forcing (ZF) equalization in the receiver's antenna. Thus, the received symbol becomes:

$$x = \frac{h^*}{|h|^2} y = s + w^{'} \text{ where } w^{'} = \frac{h^*}{|h|^2} w.$$

Finally, we need to perform Hard Decision Decoding (HDD) to detect the correct symbol as following:

$$\Re\{x\} = s + \frac{1}{|h|} w.$$

1.4.2 Alamouti CoMP

The Alamouti CoMP transmission mode has been developed in order to provide transmit diversity to the users. We consider that the BS's are connected with a central unit (CU) via links of unlimited capacity and zero latency in a way that they can exchange information about the symbols they will transmit. This is the only mode where the cooperation between the BS's is necessary. Consider two data symbols $s1$ and $s2$ going to be transmitted from BS_1 and BS_2 accordingly to user$_\mathrm{k}$ in two consecutive time slots.We also consider that channel gain remains stable for the time of two slots. So, in the first slot, the received signal in user$_\mathrm{k}$ is:

$$y_1 = h_1 s_1 + h_2 s_2 + w_1.$$

In the second slot, the received signal in user$_\mathrm{k}$ is:

$$y_2 = -h_1 s_2^* + h_2 s_1^* + w_2,$$

where $h_1 \sim \mathcal{N}(0,1)$ is the channel between BS_1 and the $\mathrm{user_k}$, $h_2 \sim \mathcal{N}(0,1)$ is the channel between BS_2 and the $\mathrm{user_k}$, $s_1, s_2 \sim (0,1)$ are the transmitted symbols and $w_1, w_2 \sim \mathcal{N}(0, N_0)$ is the white Gaussian noise on 1st and 2nd time slots as denoted before.

As mentioned in the DT mode, we must equalize our signal at the receiver side. For that purpose, we need to define the pseudo inverse matrix $H^+ = (H^T H)^{-1} H^T$ where $H = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}$.

So, the received symbols at $\mathrm{user_k}$ can be specified as:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = (H^T H)^{-1} H^T \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} w_1^{'} \\ w_2^{'} \end{bmatrix}, \text{ where } \begin{bmatrix} w_1^{'} \\ w_2^{'} \end{bmatrix} = (H^T H)^{-1} H^T \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}.$$

The HDD takes place last where the receiver decodes the two symbols independently.

1.4.3 Successive Interference Cancellation

In the SIC mode receiver antenna is able to decode packets that arrive simultaneously from the BS's. This becomes possible as the receiver can decode the stronger signal first, subtract it from the combined signal and decode the weaker one from the residue. To be more precise, the received signal at the receiver side is:

$$y = h_1 s_1 + h_2 s_2 + w.$$

Consider $|h_1| > |h_2|$, ie channel h_1 is stronger than h_2, so $equal1 = \frac{h_1^*}{|h_1|^2} y$. After decoding $s1$ with HDD, we subtract it from the combined signal, so:

$$w = y - h_1 d_1,$$

where d_1 is the decoded signal. Having the extracted signal, we equalize for the second symbol:

$$equal2 = \frac{h_2^*}{|h_2|^2} w$$

and we decode it with HDD as previously which leads to d_2.

1.5 Problem Formulation & Solution Approach Based on Instantaneous SIC Performance

1.5.1 Problem Formulation

The objective of the *resource block allocation and transmission mode selection (RBATMS)* optimization problem is to maximize the throughput in the complete HetNet in a proportional fair way. The optimization variables are defined next. Let $x_{jiklm1} \in \{0,1\}$ indicate whether BS j transmits to user i at RB k

with MCS l, the MBS uses MCS m, and that the received signal from the MBS has higher energy/bit than the signal from the PBS. Also $x_{jiklm2} \in \{0,1\}$ indicates the opposite case. $j, r \in \mathcal{R}_i$) (b) the *resource allocation* vector for all users $\boldsymbol{z}_j^{\text{ABS}} = \left(z_{jir}^{\text{ABS}} \geq 0 : j \in \mathcal{J}, i \in \mathcal{N}_j, r \in \mathcal{R}_i\right)$. Similarly the *resource allocation* vector for the regular slots. Also the global resource partitioning decision has to be made byt the HCN, i.e. $\eta = (\eta \geq 0)$. To minimize the notation later in our solution, we also define different concatenations of the variable vectors as follows: $\boldsymbol{z}_j = \left(z_{jir}^{\text{ABS}}, z_{jir}^{\text{RS}} \geq 0 : i \in \mathcal{N}_j, r \in \mathcal{R}_i\right)$, $\boldsymbol{z} = \left(z_j \geq 0 : j \in \mathcal{J}\right)$, and similarly for $\boldsymbol{x}_j, \boldsymbol{x}$.

Ideally if we were able to know perfectly the channel gains of every channel, then we could make the optimal allocation of RBs, and MCS to the users in a centralized fashion as for example in [5]. Formally, the objective of this problem is:

$$\max_{\boldsymbol{x}} \sum_{j \in \mathcal{J}-0} O_j + O_0$$

In the above we have defined:

$$\begin{aligned} O_j &= \sum_{i \in \mathcal{N}_j} \log\Big(\sum_{k \in \mathcal{K}} \sum_{l \in \mathcal{L}} \sum_{m \in \mathcal{M}} \left(x_{jiklm1} C_{jikl}^{\text{PUE1}} + x_{jiklm2} C_{jikl}^{\text{PUE2}}\right)\Big) \\ O_0 &= \sum_{i \in \mathcal{N}_0} \log\Big(\sum_{k \in \mathcal{K}_i} \sum_{m \in \mathcal{M}} x_{0ikm} C_{0ikm}^{\text{MUE}}\Big) \end{aligned}$$

With this formulation the k-th RB is re-used by every BS. Note that the objective is not a linear program because of the log, but it is however convex w.r.t. $\boldsymbol{x}$. Note also that we follow a different but equivalent optimization path that allows decoupling of the problem across the MBS and the several PBSs.

Now let us shift our attention to the formulation of the constraints. The MBS allocates to one user i and one MCS m the specific RB k:

$$\sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{N}_0} x_{0ikm} \leq 1, \ \forall k \in \mathcal{K} \tag{1.7}$$

According to OSIC one of the two signals will have the highest energy/bit and so it will be decoded first. Hence, we have:

$$x_{jiklm1} + x_{jiklm2} \leq 1, \ \forall j \in \mathcal{J}, i \in \mathcal{N}_j, k \in \mathcal{K}, l \in \mathcal{L}, m \in \mathcal{M} \tag{1.8}$$

For one RB k only a specific combination of MCSs l, m can be used, and also by a single user i (this makes the previous constraint redundant in practice):

$$\sum_{i \in \mathcal{N}_j} \sum_{l} \sum_{m} x_{jiklm1} + x_{jiklm2} \leq 1, \ \forall j \in \mathcal{J}/\{0\}, k \in \mathcal{K} \tag{1.9}$$

Also the coupling of the MBS and PBS decision variables occurs through the selection of the transmission mode m for RB k. E.g. if the MBS decides to use for RB k mode m this is the mode that the PBS has to work with OSIC. Hence:

$$x_{jiklm1} + x_{jiklm2} \leq \sum_{i \in \mathcal{N}_0} x_{0ikm} = r_{0km},$$
$$\forall j \in \mathcal{J}, i \in \mathcal{N}_j, k \in \mathcal{K}, l \in \mathcal{L}, m \in \mathcal{M} \quad (1.10)$$

Now an important aspect of the optimization model is the proper modelling of the behaviour of OSIC at the receiver. In particular we have to convert condition (1.1) into a constraint for our problem formulation. This is where the selection of the MCS actually appears in the constraints. Thus, we have:

$$(x_{jiklm1} + x_{jiklm2})(\frac{P_{\text{PBS}}|h_{j,i,k}|^2}{N_0(2^l - 1)} - \frac{P_{\text{MBS}}|h_{0,i,k}|^2}{N_0(2^m - 1)}) \leq x_{jiklm1}\Delta,$$
$$\forall j \in \mathcal{J}, i \in \mathcal{N}_j, k \in \mathcal{K}, l \in \mathcal{L}, m \in \mathcal{M} \quad (1.11)$$

Similarly the second condition

$$(x_{jiklm1} + x_{jiklm2})(-\frac{P_{\text{PBS}}|h_{j,i,k}|^2}{N_0(2^l - 1)} + \frac{P_{\text{MBS}}|h_{0,i,k}|^2}{N_0(2^m - 1)}) \leq x_{jiklm2}\Delta,$$
$$\forall j \in \mathcal{J}, i \in \mathcal{N}_j, k \in \mathcal{K} \quad (1.12)$$

These two constraints ensures that depending on the selected MCS, a certain signal must be decoded before the other, i.e. the ensure the correct decoding order depending on the SNR/bit at the receiver. Note that when $x_{jik1} = x_{jik2} = 0$, i.e. this user in not scheduled then (1.11),(1.12) are satisfied and the constraint is effectively disabled.

Eventually the problem that must be solved is the following:

$$\max_{\boldsymbol{x}} O(\boldsymbol{x})$$
$$\text{s.t. } (1.7), (1.8), (1.9), (1.10), (1.11), (1.12).$$

This formulation effectively allows the decoupling of the problem between the PBS and MBSs but the selection of the MCS actually couples the decisions through constraint (1.10). However, we do not employ dual decomposition that would make this problem more amenable to a distributed implementation since still several practical problems would exist like CQI feedback. The problem must be solved for different values of the CQI. This means that when the channel changes, the new h for each RB must be used in (1.4) to calculate the new achievable rate. In LTE we have such feedback mechanisms. However, next we investigate an even simpler approach that as we will show performs very well in practice.

1.6 Performance Evaluation

Simulation Parameters. The parameter settings for our simulations are set as follows. Downlink MBS and PBS transmit power are equal to 46dBm and 30dBm respectively. Distance-dependent path loss is given by $L(d) = I + 37.6\log_{10}(d)$, where d is the distance in Km, I=128.1 [2], and the shadowing standard deviation is 8 dB. The user speed is 3 kmph (quasi-static as we already stated). The traffic model is that of an infinite full buffer for every user, while channel estimation at the receiver is ideal. The user distribution and picocell locations are random and uniform within the complete macrocell. We implemented the proposed optimization and we evaluated its performance in terms the overall network throughput. We present the averaged results for 2000 packet transmissions that have a length of 1000 bits while BPSK modulation was used. The channel bandwidth is 10 MHz, while a Rayleigh fading wireless channel model was employed. Furthermore, we also assume that the noise over the wireless spectrum is AWGN with the variance of the noise to be 10^{-9} W/Hz at every node/link. The channel transfer functions between the nodes vary independently but they are characterized by the same average SNR.

1.6.1 Simulations and Results

In Fig. 1.3(a) we perceive that higher throughput is achieved by enabling all three transmission modes analysed above, regardless of the users number. In this simulation, we estimated the average throughput creating 50 random topologies including two BS's and a variable number (6 to 12) of users as shown in the y-axis. In every case our solution proposed achieves maximum throughput in the cell.

In Fig. 1.4(a) we notice that the performance of SIC generally improves as more small cells exist since then the benefits are multiplied. Of course when the number of users per small cell is increased, and the small cells are decreased, the SIC opportunities are decreased and the average performance is reduced.

However, the results also indicate that SRATMS approaches the performance of RATMS when the number of users associated to the small cell is increased. The reason for this behaviour is based on the premise developed in this paper, i.e. the PBS has several options to select/schedule and this allows optimized RB allocation in a SIC-optimal way.

In Fig. 1.5(a) we can observe that for high numbers of SNR, the SIC method achieves throughput very close to twice, comparing with Alamouti CoMP and Direct Transmission method. This fulfils our expectations since SIC method decodes two signals in one slot. Alamouti method though is way more reliable when it gets to low numbers of SNR. This is also expected as Alamouti CoMP like previously referred, is the only technique that provides diversity to users. In this Monte Carlo simulation we consider that the the channel remains stable for the coherence time of T = 10 bits. Bit Error Rate(BER) is been presented too in Fig. 1.5(b).

Fig. 1.6(a) presents a topology with two BS's(red dots) and five users(black dots) placed randomly around them. Aim is data information transmission in a way that throughput is maximized in the entire network. Below, we calculate the total throughput for each technique for every user given a random Rayleigh channel gain in every RB:

```
User 1: Coordinates[0.16,0.14]
```

```
Transmission mode selected for RB 1 :Direct Transmission from BS1
Transmission mode selected for RB 2 :Direct Transmission from BS1
Transmission mode selected for RB 3 :Direct Transmission from BS1
Transmission mode selected for RB 4 :Direct Transmission from BS2
Transmission mode selected for RB 5 :Direct Transmission from BS2
Transmission mode selected for RB 6 :SIC
Transmission mode selected for RB 7 :Direct Transmission from BS1
Transmission mode selected for RB 8 :SIC
Transmission mode selected for RB 9 :Alamouti CoMP
Transmission mode selected for RB 10 :Alamouti CoMP
Transmission mode selected for RB 11 :Alamouti CoMP
Transmission mode selected for RB 12 :Alamouti CoMP
Transmission mode selected for RB 13 :SIC
Transmission mode selected for RB 14 :Direct Transmission from BS2
Transmission mode selected for RB 15 :Direct Transmission from BS1
```

```
User 2: Coordinates[0.72,0.25]
```

```
Transmission mode selected for RB 1 :Alamouti CoMP
Transmission mode selected for RB 2 :Alamouti CoMP
Transmission mode selected for RB 3 :Direct Transmission from BS2
Transmission mode selected for RB 4 :SIC
Transmission mode selected for RB 5 :Direct Transmission from BS2
Transmission mode selected for RB 6 :Direct Transmission from BS2
Transmission mode selected for RB 7 :Alamouti CoMP
Transmission mode selected for RB 8 :Alamouti CoMP
Transmission mode selected for RB 9 :SIC
Transmission mode selected for RB 10 :SIC
Transmission mode selected for RB 11 :SIC
Transmission mode selected for RB 12 :Direct Transmission from BS2
Transmission mode selected for RB 13 :Alamouti CoMP
Transmission mode selected for RB 14 :SIC
Transmission mode selected for RB 15 :Alamouti CoMP
```

```
User 3: Coordinates[0.49,0.017]
```

```
Transmission mode selected for RB 1 :SIC
Transmission mode selected for RB 2 :SIC
Transmission mode selected for RB 3 :SIC
Transmission mode selected for RB 4 :Direct Transmission from BS2
Transmission mode selected for RB 5 :Direct Transmission from BS1
Transmission mode selected for RB 6 :Direct Transmission from BS1
Transmission mode selected for RB 7 :Direct Transmission from BS2
Transmission mode selected for RB 8 :Alamouti CoMP
Transmission mode selected for RB 9 :Direct Transmission from BS2
Transmission mode selected for RB 10 :Direct Transmission from BS1
Transmission mode selected for RB 11 :SIC
Transmission mode selected for RB 12 :Alamouti CoMP
Transmission mode selected for RB 13 :Alamouti CoMP
Transmission mode selected for RB 14 :Direct Transmission from BS2
Transmission mode selected for RB 15 :Alamouti CoMP
```

```
User 4: Coordinates[0.78,0.35]
```

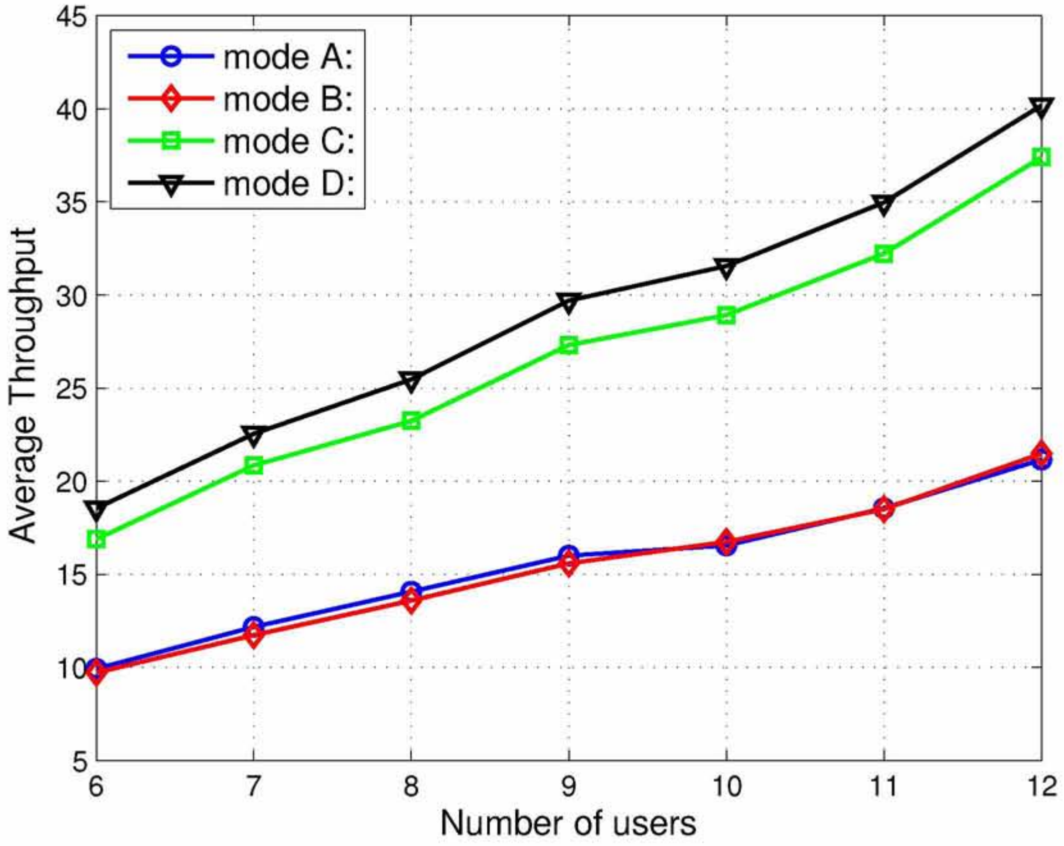
```
Transmission mode selected for RB 1 :Direct Transmission from BS2
Transmission mode selected for RB 2 :SIC
Transmission mode selected for RB 3 :SIC
Transmission mode selected for RB 4 :Direct Transmission from BS2
Transmission mode selected for RB 5 :Alamouti
Transmission mode selected for RB 6 :Direct Transmission from BS1
Transmission mode selected for RB 7 :Alamouti
Transmission mode selected for RB 8 :SIC
Transmission mode selected for RB 9 :Direct Transmission from BS2
Transmission mode selected for RB 10 :Direct Transmission from BS2
Transmission mode selected for RB 11 :SIC
Transmission mode selected for RB 12 :Alamouti
Transmission mode selected for RB 13 :Alamouti
Transmission mode selected for RB 14 :Direct Transmission from BS2
Transmission mode selected for RB 15 :Direct Transmission from BS2
```

```
User 5: Coordinates[0.81,0.98]
```

```
Transmission mode selected for RB 1 :Direct Transmission from BS2
Transmission mode selected for RB 2 :Direct Transmission from BS2
Transmission mode selected for RB 3 :SIC
Transmission mode selected for RB 4 :Direct Transmission from BS2
Transmission mode selected for RB 5 :Alamouti CoMP
Transmission mode selected for RB 6 :SIC
Transmission mode selected for RB 7 :Direct Transmission from BS1
Transmission mode selected for RB 8 :SIC
Transmission mode selected for RB 9 :Alamouti CoMP
Transmission mode selected for RB 10 :Direct Transmission from BS2
Transmission mode selected for RB 11 :Alamouti CoMP
Transmission mode selected for RB 12 :Direct Transmission from BS2
Transmission mode selected for RB 13 :Alamouti CoMP
Transmission mode selected for RB 14 :Alamouti CoMP
Transmission mode selected for RB 15 :Direct Transmission from BS2
```

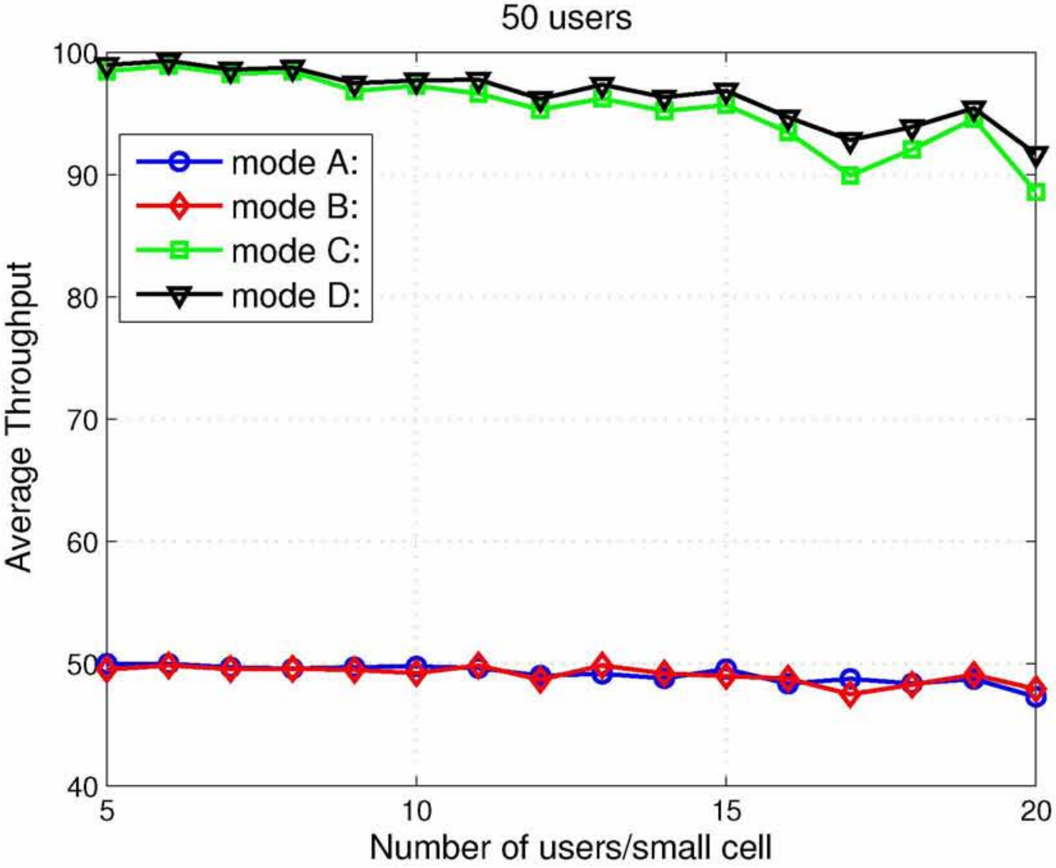
Having found the transmission mode for every user in the cell, the resource block allocation takes place. In this stage the BS's must decide in which user they will make the transmission in every resource block. Selecting the user whose technique along with his channel gain will perform the maximum throughput is the key to that decision. Below we can see the selections that BS's made:

```
RB 1 Transmit to User 3[0.49,0.01] – SIC mode: Throughput 1.0906
RB 2 Transmit to User 4[0.78,0.35] – SIC mode: Throughput 1.8187
RB 3 Transmit to User 5[0.81,0.98] – SIC mode: Throughput 2
RB 4 Transmit to User 2[0.72,0.25] – SIC mode: Throughput 1
RB 5 Transmit to User 1[0.16,0.14] – DT from BS2 mode: Throughput 1
RB 6 Transmit to User 1[0.16,0.14] – SIC mode: Throughput 1.0011
RB 7 Transmit to User 1[0.16,0.14] – DT from BS1 mode: Throughput 1
RB 8 Transmit to User 5[0.81,0.98] – SIC mode: Throughput 1.1198
RB 9 Transmit to User 2[0.72,0.25] – SIC mode: Throughput 1
RB 10 Transmit to User 2[0.72,0.25] – SIC mode: Throughput 1
RB 11 Transmit to User 2[0.72,0.25] – SIC mode: Throughput 2
RB 12 Transmit to User 1[0.16,0.14] – Alamouti: Throughput 1
RB 13 Transmit to User 1[0.16,0.14] – SIC mode: Throughput 1.3011
RB 14 Transmit to User 2[0.72,0.25] – SIC mode: Throughput 1
RB 15 Transmit to User 1[0.16,0.14] – DT from BS1: Throughput 1
```



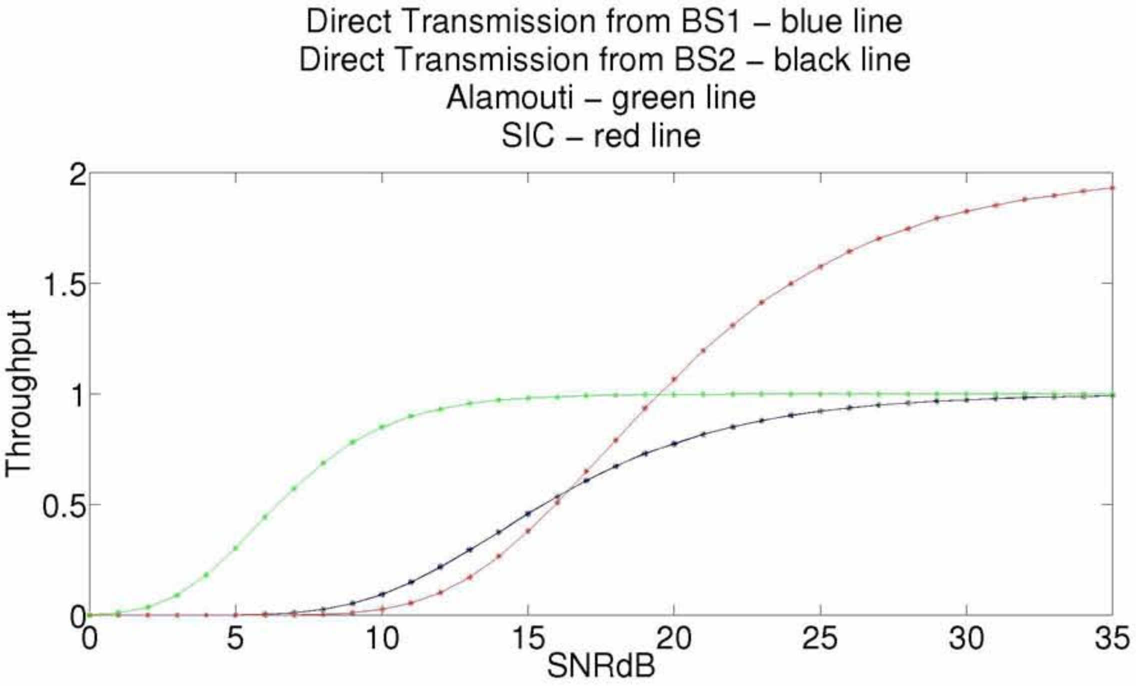
(a)

Fig. 1.3: Simulation results

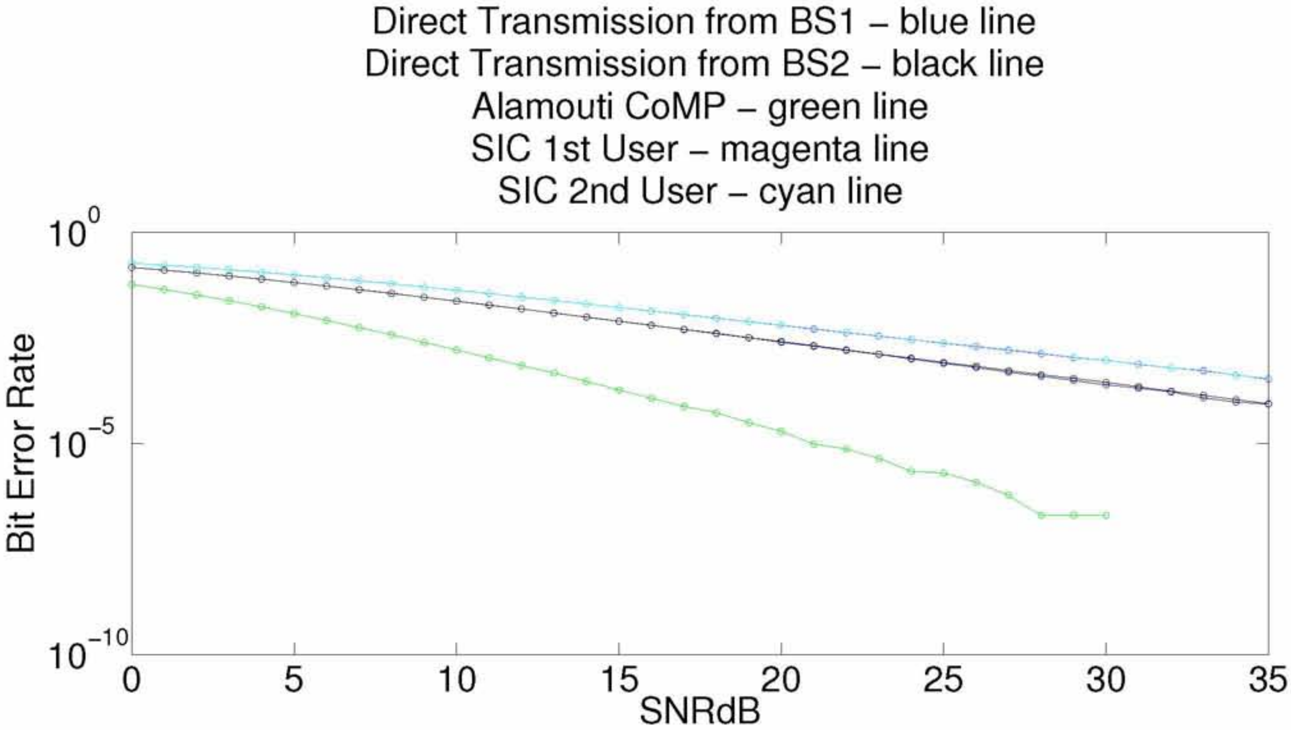


(a)

Fig. 1.4: Simulation results

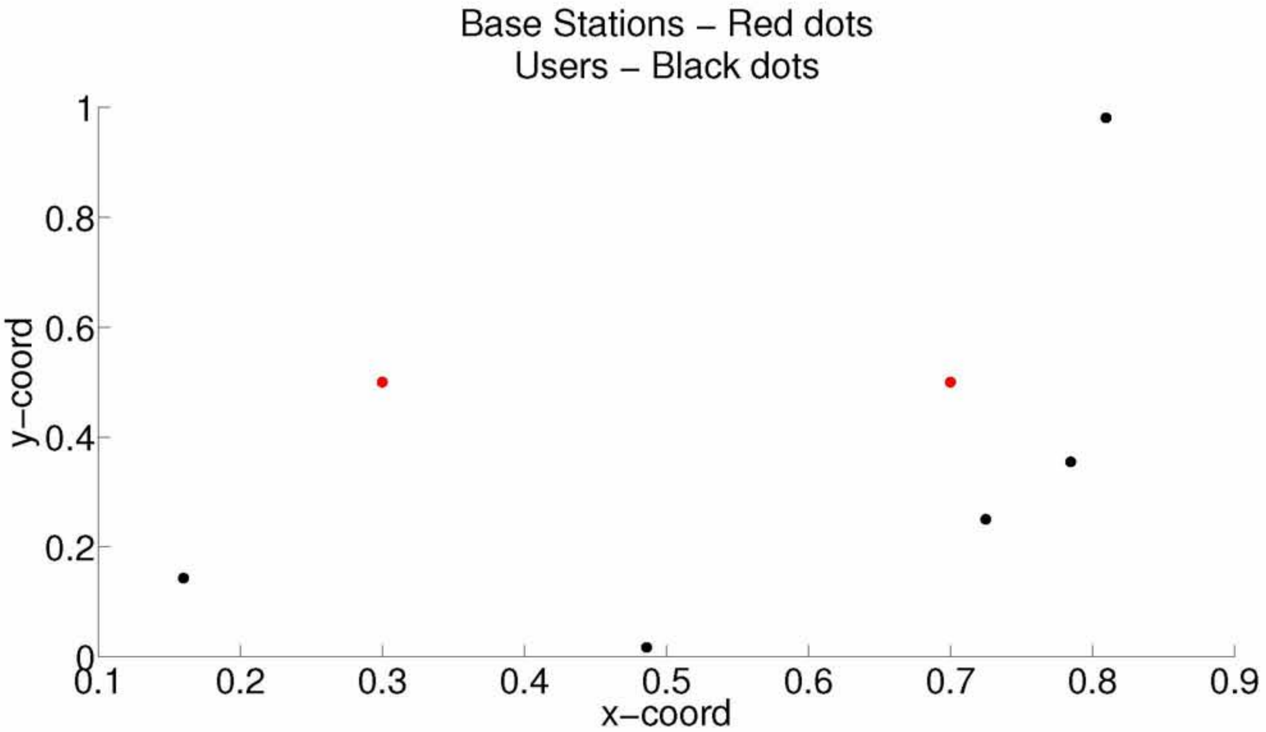


(a)



(b)

Fig. 1.5: Simulation results. Throughput - BER



(a)

Fig. 1.6: Topology of the wireless Network

BIBLIOGRAPHY

[1] J. Andrews, S. Singh, Q. Ye, X. Lin, and H. Dhillon, "An overview of load balancing in hetnets: old myths and open problems," *Wireless Communications, IEEE*, vol. 21, no. 2, pp. 18–25, April 2014.

[2] "3GPP LTE-Advanced," http://www.3gpp.org/article/lte-advanced, 2010.

[3] S. Deb, P. Monogioudis, J. Miernik, and J. Seymour, "Algorithms for enhanced inter-cell interference coordination (eicic) in lte hetnets," *IEEE/ACM Trans. on Networking*, vol. 22, no. 1, pp. 137–150, Feb 2014.

[4] S. Rangan, "Femto-macro cellular interference control with subband scheduling and interference cancelation," in *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*, Dec 2010, pp. 695–700.

[5] Y. Zhou and W. Yu, "Opportunistic joint decoding with scheduling and power allocation in ofdma femtocell networks," in *IEEE ICC*, 2012.

[6] O. Sahin, J. Li, E. Lu, Y. Li, and P. J. Pietraski, "Interference Mitigation through Successive Cancellation in Heterogeneous Networks," *ISRN Communications and Networking*, 2013.

[7] A. Adhikary, V. Ntranos, and G. Caire, "Cognitive femtocells: Breaking the spatial reuse barrier of cellular systems," in *Information Theory and Applications Workshop (ITA), 2011*, Feb 2011, pp. 1–10.

[8] A. Adhikary and G. Caire, "On the coexistence of macrocell spatial multiplexing and cognitive femtocells," in *Communications (ICC), 2012 IEEE International Conference on*, June 2012, pp. 6830–6834.

[9] K. Hosseini, J. Hoydis, S. ten Brink, and M. Debbah, "Massive mimo and small cells: How to densify heterogeneous networks," in *IEEE ICC*, June 2013, pp. 5442–5447.

[10] C. Zhang, X. Su, J. Zeng, Z. Li, and Y. Kuang, "Cross-tier cooperative transmission strategy in macro-pico heterogeneous network," in *ACM S3 workshop*, Sep 2013.

[11] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication.* Cambridge University Press, 2005.

[12] A. Argyriou, D. Kosmanos, and L. Tassiulas, “Optimizing interference cancellation in cooperative wireless networks with relay selection,” in *Information Sciences and Systems (CISS), 2014 48th Annual Conference on*, March 2014, pp. 1–5.

[13] Q. Ye, B. Rong, Y. Chen, M. Al-Shalash, C. Caramanis, and J. Andrews, “User association for load balancing in heterogeneous cellular networks,” *IEEE Trans. on Wireless Communications*, vol. 12, no. 6, pp. 2706–2716, June 2013.

[14] J. G. Proakis, *Digital Communications*, 4th ed. McGraw-Hill, 2000.