A Framework for Leakage-based Autonomous Uplink Inter-cell Interference Coordination in OFDMA/LTE Heterogeneous Networks

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Abstract: The inter-cell interference (ICI) problem in OFDMA wireless systems is a major impediment to attain high rates particularly for cell-edge users in reuse-1 systems. Using centralized resource allocation to combat ICI is not practical, particularly in heterogeneous networks (HetNets), as they require intensive signalling about interference and channel state information that may not always be practically available. The main contribution of this paper is devising efficient autonomous power allocation schemes such that the interference produced by each cell is below a certain limit. We develop two inter-cell interference coordination (ICIC) frameworks; the overall interference limit (OIL), and the interference limit per resource block (ILR). The first framework imposes an overall interference limit on each cell, while the second imposes different interference limits on different resource blocks in each cell. We propose a closed form solution, and an iterative solution for the OIL framework, and a closed form solution for the ILR framework which has an additional advantage of possible autonomous application at each terminal rather than at the base station. We present two semi-autonomous heuristic and optimal adaptive schemes that use the overload indicator (OI) signal in LTE to adjust the values of the interference limits in the ILR scheme. They attempt to alleviate the interference seen by overloaded cells in order to achieve fairness among different cells, which is very important especially in HetNets. A method based on the Kalman filter is introduced to predict the values of the OI in the intervals between the OI exchanges. This estimation can be applied to the adaptive schemes almost autonomously as it requires very infrequent signalling between cells. Simulations show that the proposed schemes exhibit better performance than equal power allocation. Comparison with centralized optimal allocation that uses global information shows good performance with acceptable degradation in the spectral efficiency which decreases as the interference limit increases. Simulations also show that the ILR and the OIL schemes almost have the same performance, and the adaptive schemes achieve fairness among different cells especially in a HetNet environment.

1 Introduction

In OFDMA-based systems, the available bandwidth is divided into a number of orthogonal subcarriers to mitigate the effect of frequency selective fading. In this paper we adopt, without loss of generality, LTE system definition of resource block (RB) comprised of a number of consecutive subcarriers (12 in LTE). A RB represents the minimum bandwidth allocation unit. The orthogonality of RB assignment in each cell eliminates the intra-cell interference; however, the inter-cell interference (ICI) problem becomes a major impediment to attaining high rates particularly for cell-edge users in reuse-1 systems. The interference generated by terminals in the neighboring cells dramatically deteriorates the signal to interference and noise ratio (SINR) received at any base station (BS), and hence decreases the rates of the cell users particularly the cell edge users. Interference mitigation techniques attempt to combat ICI by using proper resource allocation schemes. Resource allocation can generally be formulated as a weighted throughput maximization problem, but the ICI makes the rates achieved in neighboring cells be highly interdependent, and consequently most of the resource allocation problems are non-convex. In [1], it is proved that the duality gap of non-convex weighted rate maximizing problems in multicarrier systems goes to zero if the system satisfies a time sharing condition. Hence, the non-convex problem can be solved with much less complexity in its dual form. This result is used to reduce the complexity of the optimal spectrum balancing algorithm for DSL [2] by showing that the dual updates can be done effectively using the sub-gradient or the ellipsoid methods. In [3], a benchmark centralized power allocation named MARL is proposed. It converges to the global optimal of maximizing a non-concave, but monotonic, power control problem with minimum rate constraints in multicarrier multiuser networks. The proposition of this work is to formulate the problem as a monotonic optimization problem and to closely approximate the boundary of the feasible SINR region by a sequence of shrinking polyblocks. The authors use the same polyblocks strategy to solve the weighted throughput maximization power allocation problem with minimum rate constraints by reformulating the problem as a special form of generalized liner fractional programming (GLFP) in [4]. However, using centralized resource allocation is not practical, particularly in HetNet environments, as these allocations require intensive signalling of interference, and channel state information that may not always be practically available. This is why most research work focuses on developing efficient distributed allocations, while using centralized allocations as benchmarks for performance evaluation.

A lot of research work has tackled the allocation problem for downlink inter-cell interference coordination (ICIC) because it is simpler as the locations and the transmission power of the interferers are known. Also, the channel between any typical terminal and the downlink interferers can be estimated through downlink pilots. The allocation schemes can be classified as coordinated-distributed, semi-autonomous, and autonomous [5]. The uplink ICIC problem has also been tackled but less extensively. A framework for uplink power control to mitigate interference is proposed by Yates [6] using the definition of interference function. In [7], Foschini and Miljanic prove the exponential convergence of a class of distributed uplink-downlink power control algorithms aiming to achieve a minimum SINR per user as long as the set of the required SINRs is feasible. Due to the prohibitive complexity of the optimal solution, most schemes seek a heuristic suboptimal allocation that achieves near optimal results with much less complexity. The following subsection provides more in-depth coverage of the uplink ICIC problem.

1.1 Related Work in Uplink ICIC

The uplink ICIC is not easily done in an autonomous or even distributed fashion because of the highly complex interdependence between the resource allocation in every cell and the interference seen by its neighbors. This requires extensive information exchange between neighboring cells and thus a trade-off between optimality of the allocation scheme and the amount of signalling between cells arises.

Authors in [8] propose an iterative RB assignment which assigns each terminal the RBs that maximize the total utility gradients of the cell terminals, and any two terminals in two neighboring cells are allowed/prevented from transmitting on the same RB according to a defined marginal utility function. The algorithm requires extensive signaling as it uses successive pairwise coordination between cells. Moreover, the limit to which pairs of cells are grouped and the criterion showing which terminals need to be coordinated are not defined. In [9], the authors propose a downlink resource allocation scheme to maximize the weighted sum rate of the system over every RB by iteratively solving the Karush–Kuhn–Tucker (KKT) equations or by using the Newton's method. In this scheme, each BS exchanges interference price messages with its neighbors. These prices depend on the ratio between the direct and the interfering channel gains. The authors use the principle of the downlink duality (the rate region of the uplink and downlink are the same for the same power constraint) to validate their work as a suboptimal scheme for uplink allocation. Although knowing the interfering channel is a reasonable assumption for the downlink, it is not practical for the uplink unless neighboring cells exchange information about their RB assignment, which increases the amount and the frequency of signaling between cells.

Also, in [10] a five-steps multi-sector-gradient scheme that needs infrequent exchange of interference cost messages between sectors is proposed. Each sector maximizes its utility function while considering the degradation that it causes to the utilities of the neighboring sectors. The resources allocated to each user are power, sub-band, and RBs in the sub-bands. To relax the required accuracy of interference estimation, the algorithm uses the average interference instead of the instantaneous interference. They assume the interference on a subband is uniform over its RBs, and the power transmitted on RBs in the same subband is the same. In [11], an autonomous iterative water-filling resource allocation is introduced. The authors bound the egress interference of each BS in order to reduce the interference caused by each cell to its neighbors. They assume a fully homogeneous and symmetric deployment such that the average egress interference of a BS is the same as the average of the interference seen by it. So limiting the egress interference should limit the average ingress interference. The algorithm has no constraint on the maximum uplink power transmission, and it assumes that the uplink interference seen by each BS is known. The algorithm also allocates each terminal a total uplink power and a fraction of the available resources, but it does not indicate which RB should be assigned to which terminal or how power should be divided among RBs. Thus it does not utilize the discrepancies between the terminals' locations and the channel variation of each RB. A constrained noise rise density algorithm, which specifies an egress interference constraint for each RB, is also proposed. This algorithm allows the terminal with maximum weighted rate to transmit on all the RBs with the maximum power that satisfies the interference constraint. The authors of [12] propose a quality of service (QOS) aware radio resource management framework for the LTE uplink. They use closed loop power control combined with an imposed overall interference limit on the amount of interference produced by each cell to help mitigate the ICI in an autonomous fashion. They use an iterative scheme to find the required number of RBs by each terminal in order to satisfy its required rate, load it with the appropriate MCS, and calculate the uplink power of the terminal using closed loop fractional power control (CL-FPC) such that the closed loop corrective factor guides each terminal not to exceed a certain amount of interference. This algorithm needs several message exchanges between the terminals and their serving BSs in the iterative scheme until they converge to the required resource allocation. The FPC parameters like P_o and α still needs to be optimized, and the framework assumes that the terminal transmits with EPA on all the assigned RBs which does not make use of the variations of the channel gain on different RBs.

Other works model the resource allocation problem in multiuser systems as cooperative game theory between terminals. An iterative cooperative game theory approach is proposed in [13]. Every user plays in turn to select the subcarrier that reduces the interference it sees and the interference it produces using exhaustive search. An extra constraint is added to eliminate the dominant state in which each user transmits on a single subcarrier, which is not the best strategy from the viewpoint of spectral efficiency (SE). Power is allocated to satisfy a predetermined SINR and maximum power constraint. Ref. [14] extends the work of [15], which introduces bargaining between users in OFDMA systems on the intra-cell scheduling level, to an inter cell bargaining between cell edge users in order to maximize certain utilities. They also associate their inter-cell bargaining scheme with load balancing handovers to improve its performance. This bargaining works as a dynamic reuse, in which the reuse factor of the cell edge RBs is determined by the Nash bargaining. The cooperative game theory approach requires extensive signalling between cells due to the cooperation either between all terminals in different cells or between cell edge terminals in every cell as in [14].

1.2 Summary of Contributions

As seen from the above discussion on uplink ICIC, it is obvious that previous work requires extensive channel-state information exchange or makes unrealistic simplifying assumptions. This paper provides a framework for autonomous and semi-autonomous uplink ICIC that overcomes these limitations and can be adopted for application in HetNet environments. We present a new convex formulation of the resource allocation problem for autonomous ICIC in the uplink of OFDMA-based and OFDMA derivative systems (such as single-carrier frequency division multiple access SCFDMA) and proposes alternative solution techniques for it. Without loss of generality, we focus on OFDMA systems where differences with SCFDMA can be easily handled in the phase of the RB allocation which has the additional constraint of contiguity in SCFDMA systems such as LTE, so we focus the discussion on the power allocation. We define the leakage power (which is related to the egress interference in [11]) as the total power leaked by the cell to its neighbors. We use the large-scale parameters (pathloss and shadowing) between the cell users and the neighboring BSs to calculate the leakage power as these parameters can be easily estimated through downlink pilots assuming TDD. The leakage power is considered as a measure of the interference produced by the cell.

The main idea of our work is based on the notion of setting a limit to the interference produced by the cell on its neighbors. If each cell limits its interference to neighbors, it will also get a similar treatment from the neighbors, and therefore the interference that each cell sees will be limited. Instead of maximizing the terminals' uplink SINR which requires coordination between cells, we maximize the sum of the signal to noise and leakage ratios (SLNR) of the cell terminals subject to constraints on the maximum uplink power budget per terminal and a constraint on the leakage power of the cell. We present two frameworks for the autonomous uplink ICIC; the *Overall Interference Limit* (OIL) framework, and the *Interference Limit Per RB* (ILR) framework. The RB assignment is independent of the proposed power allocation schemes so any RB assignment can be used. This independence validates our work for uplink SCFDMA systems like LTE.

In the *Overall Interference Limit* (OIL) framework which we proposed in [16] , we define an overall interference limit for the whole cell. We propose a suboptimal scheme that provides a closed-form power allocation, and we also use the penalty function approach to propose an iterative power allocation using Newton's method. The two proposed power allocation schemes depend on the channel gains between the cell terminals and their serving BS over different RBs, the large scale parameters with the neighboring BSs, the interference limit, and the maximum uplink power per user. These parameters are readily available at each BS as a result of normal handover process information collection, and do not need to be exchanged among cells. Thus each cell assigns RBs and allocates power to its terminals in a completely autonomous fashion as in single-cell scheduling because it does not need to know the resource allocation or the channel conditions in other cells.

In the *Interference Limit per RB* (ILR) framework, we define different interference limits for different RBs in each cell instead of one overall interference limit for the whole cell. We derive a closed-form suboptimal power allocation scheme using this framework. This allocation can be calculated by each terminal autonomously rather than at the BS. We also propose two semi-autonomous heuristic and optimal schemes for adapting the interference limit. These adaptive schemes use the OI signal in the LTE standard [17] to adapt the values of the interference limits for every RB in each BS so as to lessen the interference seen by the overloaded BSs, and hence achieve fairness among BSs. This behavior is important to achieve fairness among different tiers in HetNets. Due to the slow exchange of OI between cells, we propose an estimation scheme, based on the Kalman filter, to estimate the values of the OI in the intervals where there is no OI update. This estimation can be done almost autonomously because it only requires very infrequent coordination between cells when applied to the adaptive ILR scheme.

Simulation results show that the SE of the system increases if we allow the cell to produce more interference. The suboptimal and the iterative allocation schemes of the OIL framework perform better than equal power allocation (EPA) especially at low interference limits. We also compare their performance with centralized utility maximization scheme based on difference of convex functions (DC) programming [18]. They exhibit acceptable performance compared with the centralized power allocation while using only local information with much less computational complexity particularly the suboptimal schemes.

Simulations also show that the ILR suboptimal scheme almost achieves the same SE as the OIL suboptimal scheme with the advantages of being autonomous on a per-terminal basis, and being easily adjusted to the network conditions via the two newly proposed adaptive schemes based on the LTE OI message. Our schemes performance is close to the CL-FPC when using PF RB assignment (each terminal is given its best RBs), but they outperform CL-FPC in case of random RB assignment when each terminal is assigned a mix of good and bad RBs. The SC-FDMA nature of the LTE might not allow each terminal to be assigned its best RBs because they might not be contiguous, so the terminal is more probably to be assigned good and bad RBs. Therefore the random RB assignment is a more realistic assumption. The heuristic and the optimal adaptive schemes improve the fairness achieved among BSs on a per-RB basis by increasing the rates achieved by the overloaded BSs and achieve higher SE than the static schemes at low interference limits. They also achieve fairness among macro and pico cells in HetNets.

The rest of this paper is organized as follows: section 2 presents the system model. Section 3 discusses the OIL framework and its proposed autonomous suboptimal and iterative allocation schemes, while section 4 discusses the ILR framework and its proposed suboptimal allocation scheme. Section 5 proposes two semi-autonomous adaptive schemes based on exploiting the Overload indicator (OI) signal, and the Kalman estimation of the OI signal. Section 6 provides performance evaluation of the proposed schemes, and section 7 concludes the paper and discusses potential future work.

2 System Model

Consider an OFDMA-based cellular system consisting of a set of M BSs as shown in Figure 1, let the set of served terminals be defined by I and the set of terminals served by BS $s \in M$ be defined by I_s. Let the function $|\,.\,|$ denotes the cardinality of the set, then we have $|I| = \sum_{s\in M}|I_s|$. Let the home/serving BS for user i be denoted by $s(i)$. Assume K to be the number of uplink RBs. Let the large-scale channel gain (path-loss and shadowing) between terminal i and BS-s, $s \in M$ and $i \in I$ be denoted by $g_{s,i}$, and let $h_{i,k}^{s}$ denotes the channel gain between terminal i and its serving BS $s(i)$ on RB-k. The value of $h_{i,k}^{s}$ reflects both large-scale channel gains and small-scale frequency-dependent fading component due to multi-path and frequency selectivity due to the variation of the channel response at the different RB's. Let $\sigma_{s,k}^2$ be the noise power on RB-k at BS-s. Furthermore, let the indicator variables $\delta_{i,k} \in \{0,1\}$ be equal to '1' if RB-k is allocated to terminal i and '0' otherwise, and $p_{i,k}$ be the uplink power transmitted by terminal i on RB-k.

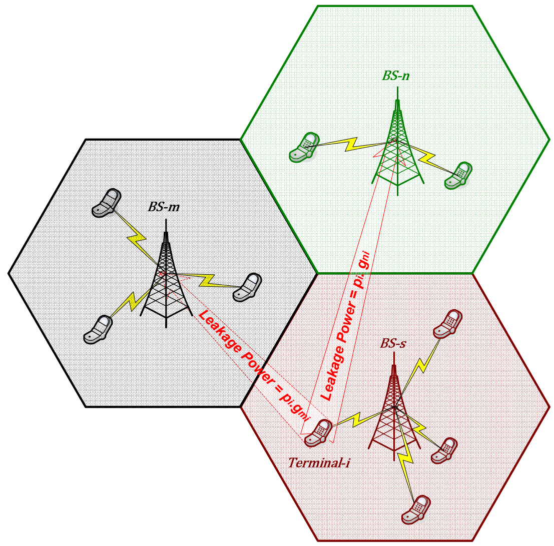

Figure 1: System model illustrating the concept of leakage power to neighboring cells

3 The Overall Interference Limit (OIL) based ICIC Framework

This section summarizes our OIL framework first presented in [16]. Subsection 3.1 presents the OIL optimization problem formulation, and subsection 3.2 introduces the proposed OIL allocation schemes.

3.1 SLNR-based Optimization with Overall Interference Limit Problem Formulation

First, we define the SLNR, which is the ratio of the received signal strength to the sum of the noise and total leaked interference to other cells. Equation (1) shows the SLNR of terminal-*i* transmitting with power $p_{i,k}$ on RB-k at BS $s = s(i)$.

$$\zeta_{i,k} = \frac{p_{i,k} h_{i,k}^{s}}{\sigma_{s,k}^{2} + p_{i,k} \sum_{n \in M, n \neq s} g_{n,i}} = \frac{p_{i,k} h_{i,k}^{s}}{\sigma_{s,k}^{2} + p_{i,k} G_{s,i}} \quad (1)$$

The term $p_{i,k} g_{n,i}$ represents the power received at BS-*n* due to terminal-*i* transmitting with power $p_{i,k}$ over RB-k (see Figure 1 for illustration). This term represents an amount of power "leaked" to BS-*n*, which affects the SINR at that BS. Therefore, the lower this value the lower the expected contribution to the interference at the neighbours of BS-*s* and the better the quality of their links. Thus, it is always desirable to have a high SLNR as this typically translates to a high SINR. $G_{s,i}$, which is the sum of the large-scale channel gains between a terminal and its neighbouring BSs, is considered the overall leakage power density of terminal-i that is served by BS-s on its neighbours.

We formulate the OIL autonomous uplink ICIC problem as in (2). U_s is the utility function of BS-*s*. We set it as the negative sum of SLNR for all terminals in BS-s over all RBs. T_s is the interference limit of BS-s, and P_{max} is the maximum uplink power allocated per terminal. The first constraint is the overall interference constraint contributed by terminals in BS-*s* to all other uplink transmissions in the system, whereas the second constraint is the total uplink-power-transmission constraint per terminal. Additional minimum rate constraints can be defined on the overall rate of each terminal-i.

$$\text{Minimize}$$

$$U_s = -\sum_{i \in I_s} \sum_{k=1}^{K} \frac{p_{i,k} h_{i,k}^{s} \delta_{i,k}}{\sigma_{s,k}^2 + p_{i,k} G_{s,i}} \; \forall s \in M$$

$$\text{Subject to} \tag{2}$$

$$F_s = \sum_{i \in I_s} G_{s,i} \sum_{k=1}^{K} p_{i,k} \delta_{i,k} \leq T_s$$

$$\sum_{k=1}^{K} p_{i,k} \delta_{i,k} \leq P_{max} \;\; \forall i \in I_s$$

This problem is also guaranteed to be convex since the second derivative of the objective function is always positive semi-definite [19]. This is an interesting formulation that removes the need for exchanging interference costs or measuring of mutual interference levels among the neighbouring BSs because it exploits the SLNR to guide the uplink power allocation problem.

3.2 The Proposed OIL ICIC Schemes

3.2.1 The OIL Suboptimal Power Allocation Scheme

Using the KKT conditions gives an optimal, yet not closed form, allocation because the KKT equations need to be solved iteratively to get numerical values for the optimal Lagrange multipliers. Instead, we relax one of the complementary slackness conditions to have a closed form suboptimal power allocation. Assume the total interference constraint is set to equality at the optimal power allocation, whereas all power constraints are set to strict inequality. This is a reasonable assumption for practical situations because the problem appears when the terminals have to reduce their transmission power to limit the produced interference not when they are allowed to transmit with their maximum power because power becomes a scarce resource that should be used wisely, and this is why it is both logical and practical that the interference constraint should be the one taken into account and the maximum power constraint is the one that is relaxed when choosing to relax one of the conditions. Beside that we use a power normalization step at the end of power allocation to make sure it satisfies the sum power constraint. This relaxation gives the following closed form autonomous power allocation. For detailed derivation of the results, we refer the reader to our previous work in [16].

$$p_{i,k} = \max\left(\frac{1}{G_{s,i}}\left[\sqrt{\frac{\sigma_{s,k}^2 h_{i,k}^s}{\mu^* G_{s,i}}} - \sigma_{s,k}^2\right], 0\right),$$

$$\mu^* = \left(\frac{\sum_{i\in I_s}\sum_{k=1}^{K}\delta_{i,k}\sqrt{\frac{\sigma_{s,k}^2 h_{i,k}^s}{G_{s,i}}}}{T_s + \sum_{i\in I_s}\sum_{k=1}^{K}\delta_{i,k}\sigma_{s,k}^2}\right)^2 \quad (3)$$

$$k = 1, 2, \dots, K, i \in I_s.$$

3.2.2 The OIL Log-barrier Iterative Power Allocation Scheme

We reformulate the problem by assigning a logarithmic penalty function for each constraint. This approach converts the inequality constrained optimization problem in (2) to the following unconstrained problem in (4) where both η^T and $\eta_i^p \geq 0$ and are chosen as small as possible. The optimization problem in (4) is convex and can be solved using a multitude of methods such as Newton's method. For details of the solution method, we refer the reader to our previous work [16].

$$\text{Minimize}$$

$$f(\vec{P}) = f_0(\vec{P}) + f_T(\vec{P}) + \sum_{i\in I_s} f_{c,i}(\vec{P}) \quad (4)$$

$$= -\sum_{i\in I_s}\sum_{k=1}^{K}\frac{\delta_{i,k}p_{i,k}h_{i,k}^s}{\sigma_{s,k}^2 + p_{i,k}G_{s,i}} - \eta^T \log\left(T_s - \sum_{i\in I_s} G_{s,i}\sum_{k=1}^{K}\delta_{i,k}p_{i,k}\right) - \sum_{i\in I_s}\eta_i^p \log\left(P_{max} - \sum_{k=1}^{K}\delta_{i,k}p_{i,k}\right)$$

4 The Individual Limit per Resource Block (ILR) based ICIC Framework

4.1 SLNR-based Optimization with Interference Limit per RB Problem Formulation

We consider the same convex optimization problem of the OIL framework in (2) which maximizes the sum of the individual SLNRs of terminals in BS-s subject to sum power constraints per terminal and an overall interference constraint for the whole cell. We minimize the same objective subject to the same maximum power constraint, but we use different interference constraints for different RBs instead of one overall interference constraint for the whole cell. Each cell in this new formulation is allowed to have a different interference limit for every RB $T_{s,k}$ which is the interference limit of BS-s on RB-k . The new formulation is defined as follows:

$$\text{Minimize}$$

$$U_s = -\sum_{i\in I_s}\sum_{k=1}^{K}\frac{p_{i,k}h_{i,k}^s\delta_{ik}}{\sigma_{s,k}^2 + p_{i,k}G_{s,i}} \quad \forall s \in M \quad (5)$$

$$\text{Subject to}$$

$$\sum_{k=1}^{K} p_{i,k}\delta_{ik} \leq P_{max} \ \ \forall i \in I_s$$

$$\sum_{i=1}^{|I_s|} p_{ik}G_{s,i}\delta_{ik} \leq T_{s,k} \quad \forall k = 1,2,\dots,K, i \in I_s$$

The second constraint couples the powers transmitted by all the cell terminals on RB-k. This coupling hinders solving the problem independently at each terminal because the Lagrange multipliers associated with each RB should be exchanged between the cell terminals. However, practically, we know that each RB is assigned to only one terminal, thus the second constraint could be rewritten as a maximum power constraint per RB, and the optimization problem becomes as follows:

$$\begin{gathered} \text{Minimize} \\ U_s = -\sum_{i \in I_s}\sum_{k=1}^{K} \frac{p_{i,k}h_{i,k}^{s}\delta_{ik}}{\sigma_{s,k}^2 + p_{i,k}G_{s,i}} \ \forall s \in M \\ \text{Subject to} \\ \sum_{k=1}^{K} p_{i,k}\delta_{ik} \leq P_{max} \ \ \forall i \in I_s \\ p_{ik} \leq \frac{T_{s,k}}{G_{s,i}} \forall k = 1,2,\dots,K \end{gathered} \tag{6}$$

4.2 The ILR Suboptimal Power Allocation Scheme

In this subsection, we solve the problem in (6) by defining the Lagrangian function as follows:

$$\begin{aligned} L(\vec{P},\vec{\lambda},\vec{v}) &= -\sum_{i=1}^{|I_s|}\sum_{k=1}^{K} \frac{p_{ik}h_{i,k}^{s}\delta_{ik}}{p_{ik}G_{s,i} + \sigma_{s,k}^2} + \sum_{i=1}^{|I_s|}\lambda_i\left[\sum_{k=1}^{K} p_{ik}\delta_{ik} - P_{max}\right] \\ &+ \sum_{k=1}^{K}\sum_{i=1}^{|I_s|} \nu_{i,k}\delta_{ik}\left[p_{ik} - \frac{T_{s,k}}{G_{s,i}}\right] \\ &= \textstyle\sum_{i=1}^{|I_s|}\left[L_i(\vec{P}_i,\lambda_i,\vec{v}_i) - P_{max}\,\lambda_i\right], \end{aligned} \tag{7}$$

where $L_i(\vec{P}_i,\lambda_i,\vec{v}_i)$ defined in (8) is the Lagrangian corresponding to terminal-i and λ_i and $\vec{v}_i$ are its Lagrange multipliers.

$$L_i(\vec{P}_i,\lambda_i,\vec{v}_i) = \sum_{k=1}^{K}\left[-\frac{p_{ik}h_{i,k}^{s}\delta_{ik}}{p_{ik}G_{s,i} + \sigma_{s,k}^2} + \delta_{ik}[p_{ik}(\lambda_i + \nu_{i,k}) - \frac{T_{s,k}}{G_{s,i}}\nu_{i,k}]\right] \tag{8}$$

The problem can now be solved independently on a terminal basis. Every terminal-i attempts to minimize the function $L_i(\vec{P}_i,\lambda_i,\vec{v}_i)$ with respect to $\vec{P}_i$. Since the function is convex over p_{ik}, the optimal power allocated to terminal-i over RB-k is calculated by equating the first partial derivative of $L_i(\vec{P}_i,\lambda_i,\vec{v}_i)$ w.r.t. p_{ik} to zero and solving for p_{ik}, from which we get:

$$p_{ik}^* = \frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \sqrt{\frac{\sigma_{s,k}^2 h_{i,k}^s}{(\lambda_i^* + v_{ik}^*)}}\right] \tag{9}$$

The complementary slackness conditions should be solved iteratively to get the optimal Lagrange multipliers λ_i^* and v_{ik}^*. This definitely does not give a closed form solution and therefore we make some approximations. By carefully inspecting the problem, we see that each terminal attempts to transmit with the maximum allowable power on every assigned RB as long as the sum power constraint is satisfied. Hence, each terminal would transmit with power $p_{ik} = \frac{T_{s,k}}{G_{s,i}}$ on every assigned RB-k. Therefore, if we assume that the maximum power constraint per RB is satisfied with very small inequality, then v_{ik}^* equals zero for all k, and the optimal power allocation becomes

$$p_{ik}^* = \frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \sqrt{\frac{\sigma_{s,k}^2 h_{i,k}^s}{\lambda_i^*}}\right] \tag{10}$$

Substituting with this new power allocation into the sum power constraint which should be satisfied with equality, the optimal Lagrange multiplier λ_i^* for terminal-i is given as follows:

$$\sqrt{\lambda_i^*} = \frac{\sum_j \sqrt{\sigma_{s,j}^2 h_{i,j}^s \delta_{ij}}}{G_{s,i} P_{max} + \sum_j \sigma_{s,j}^2 \delta_{ij}} \tag{11}$$

After substituting with λ_i^* in (10), the power allocation becomes

$$p_{ik}^* = \frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \frac{\sqrt{\sigma_{s,k}^2 h_{i,k}^s}\,(G_{s,i} P_{max} + \sum_j \delta_{i,j} \sigma_{s,j}^2)}{\sum_j \delta_{i,j} \sqrt{\sigma_{s,j}^2 h_{i,j}^s}}\right] \tag{12}$$

Considering the maximum power allowable for terminal-i on RB-k, the power allocation becomes

$$p_{ik}^* = min\left\{\frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \frac{\sqrt{\sigma_{s,k}^2 h_{i,k}^s}\left(G_{s,i} P_{max} + \sum_j \delta_{i,j} \sigma_{s,j}^2\right)}{\sum_j \delta_{i,j} \sqrt{\sigma_{s,j}^2 h_{i,j}^s}}\right], \frac{T_{s,k}}{G_{s,i}}\right\} \tag{13}$$

The advantage of this allocation is that the BS only needs to inform each terminal in the cell what RBs are assigned to it, whereas the power allocation is determined by each terminal independently. The large scale parameters $Gs,_i$ and the channel gain $h_{i,k}^s$ can be easily estimated via pilots from the serving and the neighboring BSs. If the maximum allowable power (2nd argument of the min function in (13)) is less than the first argument (calculated power) for terminal-i over all the assigned RB, then there is no problem because the terminal will transmit with the maximum allowable power on all its assigned RBs. The only problem appears if some of the assigned RBs have small maximum allowable power. In this case, we suggest a simple power correction step by adding the extra remaining power (Δ) to the RB-k that yields maximum marginal utility. This marginal utility can be simply calculated from the objective function as follows:

$$\frac{(p_{ik}+\Delta)h_{i,k}^{s}}{\sigma_{s.k}^{2}+(p_{ik}+\Delta)G_{s,i}}-\frac{p_{ik}h_{i,k}^{s}}{\sigma_{s,k}^{2}+p_{ik}G_{s,i}} \quad (14)$$

In other words, we assign the extra Δ power to RB-k, as long as $(p_{ik}+\Delta)\leq\frac{T_{s,k}}{G_{s,i}}$, where k is calculated as follows:

$$k=argmax_{j}\frac{\Delta h_{i,j}^{s}\sigma_{j}^{2}}{(\sigma_{s,j}^{2}+p_{ij}G_{s,i})(\sigma_{s,j}^{2}+(p_{ij}+\Delta)G_{s,i})} \quad (15)$$

If $(p_{ik}+\Delta)\geq\frac{T_{s,k}}{G_{s,i}}$, this means that we cannot allocate all the extra power to RB-k because it would exceed the maximum allowable power. Consequently, we allow the terminal to transmit with maximum power on this RB, and search for the second best RB using (15). We repeat the search and allocation process until there is no extra power remained or the terminal transmits with the maximum power allowable on all its assigned RBs. The very worst case (which is very unlikely to happen) is when the terminal is assigned all the *K* RBs in the cell, and *K*-1 of them still able to accept the extra power remaining from the other "one" RB. The maximum power constraints on those *K*-1 RBs allows each of them to take only part of the extra power sot the terminal would at first sort *K*-1 terminals, give some power to the first good RB, then eliminate it and sort the remaining *K*-2 RBs, and so one until only one RB is left.

In this suboptimal scheme, we assume that the values of the interference limits are known and fixed, however these values should be adapted according to the dynamic conditions of the network. In the next section, we propose a semi-autonomous heuristic scheme and an optimal scheme to adapt the interference limits of the cell over every RB by using the OI signal in the LTE standard.

5 Interference Limit Adaptation

Release 8 LTE and beyond allows the exchange of an OI message between the neighbouring BSs over the X2 interface to help acquiring information on interference for proper ICIC [17]. This signal indicates the level of interference (low/medium/high) seen by the BS per RB, and is exchanged every 20 ms. Although the signal is standardized, the action which the neighbours of an overloaded BS should take to react with an OI signal is not specified yet.

In this section we propose two schemes that adapt the interference limits in response to the OI message exchange between neighbouring cells. For simplicity, we assume that there are only two levels for the OI '0' for low interference, and '1' for high interference. When the SINR seen by a BS drops below a certain threshold, it asserts its OI to '1'. Each BS can adapt its interference limits once every 20 ms, when the values of the OIs are exchanged between cells. It can also estimate the value of the OIs of its neighbors on different RBs for the intermediate 19 ms using the Kalman filter estimation as discussed in section 5.3.

First, each BS assigns the RBs to its terminals using the proportional fair scheme, and every terminal calculates its power using the proposed ILR suboptimal formula and the proposed power allocation correction. Then, each BS checks the OI of its neighbours over all RBs. For every overloaded RB-k, the BS compares the interference contributed by its terminal to the overloaded BS on RB-k ($p_{i,k}.\,g_{Overloaded\ BS,i}$) with a threshold to determine whether this terminal is the major interferer. We assume the interference threshold to be defined by

$$I_{th} = \frac{p_{max}}{C * K} * mean(G) \tag{16}$$

which is the average power leaked by a typical terminal if it transmitted with power p_{max}/K over all RBs and C is a parameter that can be adjusted . The dependence on the large scale parameters to calculate the interference helps reducing the frequency of channel estimation between a typical terminal and its neighbouring BSs. Each BS increases its interference limit on RB-k by 50% if none of its neighbors are overloaded on this RB or if its terminal transmitting on the overloaded RB is found not to be the major interferer. On the other hand, if the terminal is governed to be the major cause of overload, we propose two schemes to adapt the power and update the interference limit as discussed in the two following subsections. For simplicity, if the cell is a major interferer for more than one overloaded neighbour on the same RB, it chooses the BS that sees the highest leakage power and considers it the victim neighbour, then the adaptive schemes are applied in a pair-wise manner.

5.1 The Heuristic Adaptive Scheme

In this scheme a further check is made to decide on the action to be taken. Assume BS-*m* to be overloaded on RB *k*, and *BS-s* to be the major interferer on the same RB. Terminals i_m and i_s are the terminals transmitting on RB-k in BS-*m* and BS-*s* respectively. Let $h^m_{i_m,k}$ and $h^s_{i_m,k}$ be the channel gains between terminal i_m and BS-m and BS-s respectively. To understand how reducing the power that terminal i_s transmits on RB-k ($p_{s,k}$) affects the rates achieved by terminals i_m and i_s , we calculate the first derivative of the rate achieved by terminal i_m on RB-k w.r.t $p_{s,k}$ and the first derivative of the rate achieved by terminal i_s on RB-k w.r.t $p_{s,k}$ which are $\frac{\partial R_{m,k}}{\partial p_{s,k}}$ and $\frac{\partial R_{s,k}}{\partial p_{s,k}}$ respectively. Using Shannon's formula, we write the rate as a logarithmic function of the SINR

$$R_{m,k} = \ln(1 + SINR_{m,k})$$
$$SINR_{m,k} = \frac{p_{m,k} h^m_{i_m,k}}{\sigma^2_{m,k} + I_{m,k}} \tag{17}$$

where $I_{m,k}$ is the interference seen by BS-m on RB-k given by $I_m = \sum_{n\neq m} p_{n,k} h^m_{i_n,k}$. Using the chain rule to calculate the first derivative

$$\frac{\partial R_{m,k}}{\partial p_{s,k}} = \frac{\partial R_{m,k}}{\partial SINR_{m,k}} . \frac{\partial SINR_{m,k}}{\partial I_{m,k}} . \frac{\partial I_{m,k}}{\partial p_{s,k}} = \Psi_{m,k}.\, h^m_{i_s,k}$$

where $\Psi_{m,k} = \frac{1}{1+SINR_{m,k}} . \frac{-p_{m,k} h^m_{i_m,k}}{(\sigma^2_{m,k}+I_{m,k})^2}$. The negative sign of $\Psi_{m,k}$ means that reducing the power transmitted by the interfering terminal in the interfering BS on the overloaded RB increases the rate achieved by the overloaded BS on the same RB, and we assume Ψ_m of the overloaded BS to be known at the interfering BS. Similarly, we calculate $\frac{\partial R_{s,k}}{\partial p_{s,k}}$ as follows:

$$
\begin{aligned}
R_{s,k} &= \ln(1+SINR_{s,k}) \\
SINR_{s,k} &= \frac{p_{s,k} h^{s}_{i_s,k}}{\sigma^2_{s,k} + I_{s,k}} \\
I_s &= \sum_{n \neq s} p_{n,k} h^{s}_{i_n,k} \\
\frac{\delta_{i,k} R_{s,k}}{\delta_{i,k} p_{s,k}} &= \frac{\partial R_{s,k}}{\partial SINR_{s,k}} \cdot \frac{\partial SINR_{s,k}}{\partial p_{s,k}} \\
&= \frac{1}{1+SINR_{s,k}} \cdot \frac{h^{s}_{i_s,k}}{\sigma^2_{s,k} + I_{s,k}}
\end{aligned}
\tag{18}
$$

The proposed heuristic scheme utilizes the available information about the victim BS to calculate a non-optimal power reduction step, we attempt to compromise between the total system rates and the fairness among BSs. We update the power transmitted by the interfering terminal and the interference limit as follows:

1:	**If** ($\left\|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right\| > \frac{\partial R_{s,k}}{\partial p_{s,k}}$),
2:	$p_{s,k} = p_{s,k} * \left\|\frac{\partial R_{s,k}}{\partial p_{s,k}}\right\| / \left\|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right\|$
3:	**else**
4:	$p_{s,k} = p_{s,k} * \left[1 - \left\|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right\| / \left\|\frac{\partial R_{s,k}}{\partial p_{s,k}}\right\|\right]$
5:	**end**
6:	$T_{s,k} = T_{s,k} - 0.5(p_{s,k} * G_{s,k})$

The if condition means that the power reduction in (step 2) yields a total sum rates of the two terminals in the major interfering BS and the victim BS that is greater than the sum rates before reduction. Therefore, the power reduction step $(p^{old}_{s,k} - p^{new}_{s,k})$ increases as the ratio $\left|\frac{\partial R_{s,k}}{\partial p_{s,k}}\right| / \left|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right|$ decreases. On the other hand the else condition means that the power reduction in (step 4) reduces the sum rates of the two terminals, and therefore the reduction step decreases as the ratio $\left|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right| / \left|\frac{\partial R_{s,k}}{\partial p_{s,k}}\right|$ decreases. This is just to lessen the load on the overloaded RB to achieve some sort of fairness among the BSs per RB. This heuristic scheme only requires the overloaded BS-m to exchange its ψ_m values embedded within the OI message with its neighbours. All the other signals that are used in the algorithm can be simply estimated by the major interfering BSs autonomously through downlink pilots.

5.2 The Optimal Adaptive Scheme

In this scheme, we calculate the optimal step Δ with which the interfering terminal in BS-s (the interfering BS) should reduce its power. For simplicity, we assume that only the major interfering terminal will change its power on the overloaded RB, whereas the other terminals in the other cells will not change their powers. Assuming information about the two BS's are known perfectly by the two or at one of them which is responsible for informing the other, we solve a pairwise optimization problem between the overloaded BS-m and the interfering BS-s. We maximize the weighed sum of $R_{s,k}$ and $R_{m,k}$, which are the rates achieved on RB-k by BS-s and BS-m respectively. The weights can be set according to any desired criterion. In the rest of this paper, we take the weights of the victim/major interferer cell as the ratio of the number of the cell's violation to the total number of the two cells' violations. The violations count the number of times that each cell is overloaded (achieves SINR lower than the SINR threshold). The problem is given as follows:

$$\begin{gathered}\text{Maximize}\\ w_s R_{s,k}\left(p_{s,k}-\Delta\right)+\ w_m R_{m,k}\left(p_{s,k}-\Delta\right)\\ \text{Subject to}\\ 0\le\Delta\le p_{s,k}\end{gathered}\tag{19}$$

The constraint assures that the new power will be reduced and will be positive as well. Reducing $p_{s,k}$ by Δ reduces the interference seen by the overloaded BS-m by $\Delta h_{s,k}^{m}$, so the problem in (19) becomes

$$\begin{gathered}\text{Maximize}\\ w_s\ln\left(1+\frac{\left(p_{s,k}-\Delta\right)h_{i_s,k}^{s}}{\sigma_{s,k}^{2}+I_{s,k}}\right)+w_m\ln\left(1+\frac{p_{m,k}h_{i_m,k}^{m}}{\sigma_{m,k}^{2}+I_{m,k}-\Delta h_{i_s,k}^{m}}\right)\\ \text{Subject to}\\ 0\le\Delta\le p_{s,k}\end{gathered}\tag{20}$$

This problem can be solved using DC programing [18] by substituting with the first order approximation of the denominator of the second term in (20) as follows:

$$\begin{gathered}\text{Maximize}\\ w_s f(\Delta)+w_m g_1(\Delta)+w_m g_2\left(\Delta^j\right)+w_m\frac{\partial g_2\left(\Delta^j\right)}{\partial\Delta}\left(\Delta-\Delta^j\right)\\ \text{Subject to}\\ 0\le\Delta\le p_{s,k}\end{gathered}\tag{21}$$

where

$$f(\Delta)=\ln\left(\sigma_{s,k}^{2}+I_{s,k}+p_{s,k}h_{i_s,k}^{s}-\Delta h_{i_s,k}^{s}\right)$$

$$g_1(\Delta)=\ln\left(\sigma_{m,k}^{2}+I_{m,k}+p_{m,k}h_{i_m,k}^{m}-\Delta h_{i_s,k}^{m}\right)$$

$$g_2(\Delta)=-\ln(\sigma_{m,k}^{2}+I_{m,k}-\Delta h_{i_s,k}^{m})$$

and

$$\frac{\partial g_2\left(\Delta^j\right)}{\partial\Delta}=\frac{h_{i_s,k}^{m}}{\sigma_{m,k}^{2}+I_{m,k}-\Delta^j h_{i_s,k}^{m}}$$

We solve this problem using the FW procedure [18] the power and the interference limit are updated as follows $p_{s,k} = p_{s,k} - \Delta, \quad T_{s,k} = T_{s,k} - 0.5[p_{s,k} * G_{s,k}]$.

The two adaptive schemes adopt a simple coordination where the major interfering cell on a certain RB coordinates with its victim neighbour only (the neighbour that receives maximum leakage power form it on that RB). The major interfering BS also updates its power and interference limit when the number of overload indicators of its victim neighbour on the overloaded RB exceeds its number of overloads on the same RB by at least 25%. This means that the worst case is that all the K RBs are overloaded and the same cell is a major interferer on all the RBs. In this case, the cell would make K coordination (1 coordination with 1 neighbour for every RB).

5.3 OI Estimation using the Kalman Filter

The main problem with the OI message is that it is exchanged between the BSs every 20 ms which means that about 19 different intra-cell scheduling occur without receiving any OI update. In this subsection, we use the concept of the Kalman filter [20] to estimate the value of the OI at each BS with minimum data exchange. The major advantage of our estimation scheme is that it is applied autonomously at each cell and it does not require extra signalling between neighbours when applied to our adaptive ILR schemes.

We consider the random variable $\gamma_{m,s,k}$ to be the inverse SINR of BS-m on RB-k estimated at BS-s such that $\gamma_{m,s,k} = \frac{\sigma^2_{m,k} + I_{m,k}}{p_{m,k*} h^m_{i_{m,},k}}$ where $I_{m,s,k}$, is the interference seen by BS-m on RB-k. The digital value of the OI seen by BS-s on RB-k can be evaluated by comparing $\gamma_{m,s,k}$ with an SINR threshold ($SINRth$) as follows

$$OI = \begin{cases} 0, & \gamma_{m.s,k} \leq {}^{1}/_{SINRth} \\ 1, & \gamma_{m,s,k} > {}^{1}/_{SINRth} \end{cases} \tag{22}$$

To estimate the value of $\gamma_{m,s,k}$ at time instant n+1 using its value at time instant n, we make the same assumption we used in section 5.2 that only the major interferer changes its power on the overloaded RB with Δ, while the other BSs do not change their powers. This assumption allows the interfering BS-s to make an apriori estimate of the interference seen by the overloaded BS-m at the next time instant as follows:

$$I^{n+1}_{m,s,k} = I^{n}_{m,s,k} - \Delta.\, h^m_{i_s,k} \tag{23}$$

and hence

$$\gamma^{n+1}_{m,s,k} = \gamma^{n}_{m,s,k} - \frac{\Delta h^m_{i_s,k}}{p_{m,k} h^m_{i_m,k}} \tag{24}$$

Since we assume in our adaptive schemes that the overloaded BS-m only exchanges information with its major interfering BS-s, then any given BS-s will update the value of $\gamma_{m,s,k}$ only when it is the major interferer of this BS. In this case the interfering BS corrects its current estimate of the inverse SINR $\gamma^n_{m,s,k} =$

$\frac{1}{SINR_{m,k}^{n-1}}$ where $SINR_{m,k}^{n-1}$ is the actual SINR of BS-m on RB-k at time instant n-1, and it makes an apriori estimation to $\gamma_{m,s,k}^{n+1}$ according to (24). Hence this estimation does not burden the system with extra signalling between cells.

6 Performance Evaluation

Subsection 6.1 evaluates the performance of the static allocation schemes, subsection 6.2 evaluates the performance of the adaptive allocation schemes, and subsection 6.4 discusses the behaviour of the adaptive scheme in a HetNet environment. Also subsection 6.3 evaluates the performance of our static schemes when using random RB assignment. The main metrics for the evaluation are the system spectral efficiency (throughput in bits/sec/Hz) and the 10-percentile throughput (maximum throughput achieved by the most unlucky 10% of terminals in system).

6.1 Results of the Static Autonomous Allocation Schemes

Consider an OFDMA-based network of four BSs located at (500,500)m,(-500,500)m, (-500,-500)m, and (500,-500)m respectively. Forty terminals are uniformly distributed over a 500m × 500m square area centered at the origin, and each terminal is served by the nearest BS. Figure 2 shows an example for the network layout; the locations of the BSs and the links between them and their served terminals. Each terminal and BS has a single omni-directional antenna. The total number of RBs is 30, and each RB consists of 12 subcarriers. We consider the typical urban macro cell scenario using the WINNER II channel model. The noise power density is -174 dBm/Hz, the maximum power allocated per terminal is 24 dBm, and the total power leaked by each cell on the neighbouring cells is constrained by an interference limit, which we vary in our simulations. We assume proportional fair (PF) RB assignment, where each terminal is assigned the best RBs it sees.

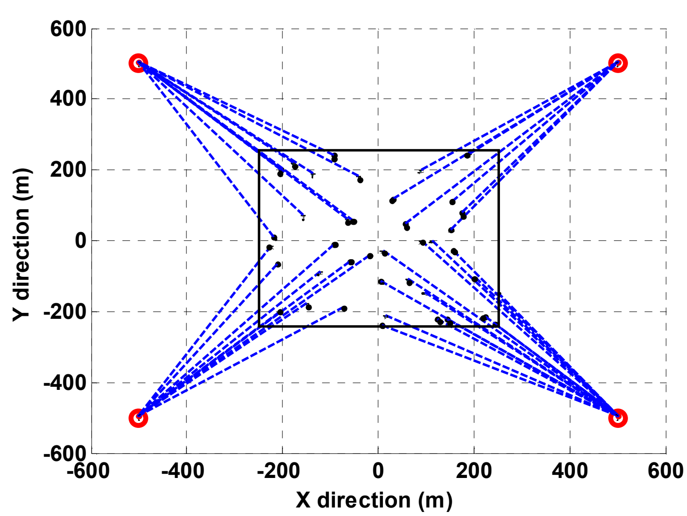

Figure 2: Network layout

Figure 3 shows the system SE of these schemes compared with the trivial EPA and the centralized allocation. We also compare our results with a CL-FPC using the mapping function for the closed loop corrective factor in [12]. We use fractional compensation factor $\alpha = 0.8$ and $P_0 = -100\ dBm$, and we also use the equal weight approach defined in [12].The proposed schemes exhibit better performance than EPA and a slightly better performance than the CL-FPC especially at low interference limit when power should be limited. They also exhibit good performance compared with the centralized power allocation that maximizes the weighted sum of the terminals' rates in the system when the weight of each terminal is taken to be the inverse of its average rate.

The OIL and ILR suboptimal schemes have close performance especially at high values of interference limits (−90:−70 dBm), while the ILR scheme exhibits lower SE at small values of interference limit. This behaviour is expected because at high interference limits the two schemes are constrained by the maximum sum power constraint, while, at small interference limits, the two schemes are constrained by different interference limit constraints, which is actually more restricting in the case of the ILR scheme. This is clarified by rewriting the interference constraint in (2) as $\sum_{=1}^{K} \sum_{i \in I_s} p_{i,k} G_{s,i} \leq \sum_{k=1}^{K} T_{s,k}$. Since each RB-$k$ is assigned to one terminal only (i_k) in the cell, then the constraint can be further simplified to $\sum_{k=1}^{K} p_{i_k,k} G_{s,i_k} \leq \sum_{k=1}^{K} T_{s,k}$. This constraint is loose because it allows terminals to transmit with high powers on the good RBs and with low powers on the bad RBs as long as the total power leaked on all RBs satisfy the constraint. On the other hand in the per RB interference limit, we force the power transmitted by user i_k on each RB-k to be less than $\frac{T_{s,k}}{G_{s,i_k}}$, and since we take $T_{s,k} = \frac{T_s}{K}$ to be equal for all RBs, we do not differentiate between good RBs and bad RBs.

Figure 4 compares the 10-percentile throughput of the different schemes at different interference limits. It is also evident that at high interference values there is not much difference between schemes, however at low interference limits the most unlucky 10% of terminals have a better chance of having higher rates in the EPA at the expense of the overall SE of the system.

Figure 5 and Figure 6 show the user SE cumulative distribution function (CDF) at interference limits -90 dBm and -110 dBm respectively. As shown, when the interference limit is -90 dBm the CDFs of the different schemes are almost the same because the terminals are allowed to transmit with maximum power and each terminal is given the best RBs it sees. This is also clear in Figure 3 as the SE is almost insensitive to variations in the interference limit beyond -90 dBm. On the other hand, when the interference limit decreases, the EPA is incapable of achieving high spectral efficiencies per user unlike the proposed static schemes which allows some terminals to achieve higher rates at the expense of other terminals which, in turn, increases the total SE than its value in EPA.

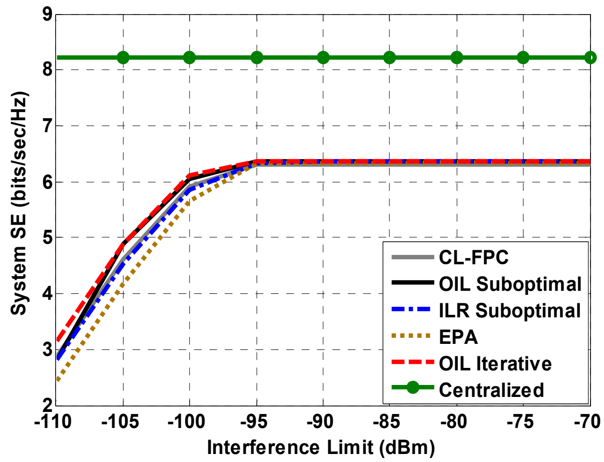

Figure 3: Spectral efficiency of the static schemes

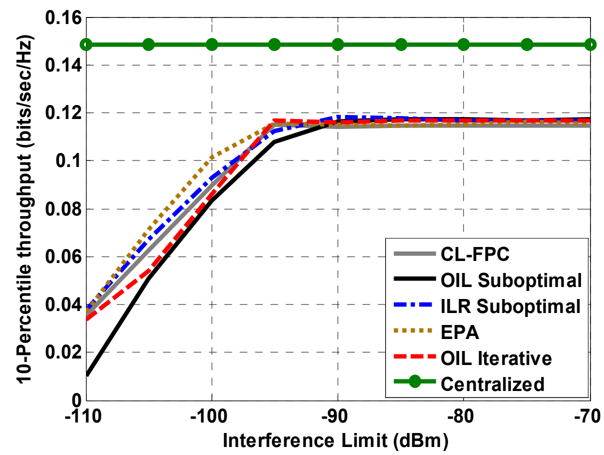

Figure 4: 10-Percentile throughput of the static schemes

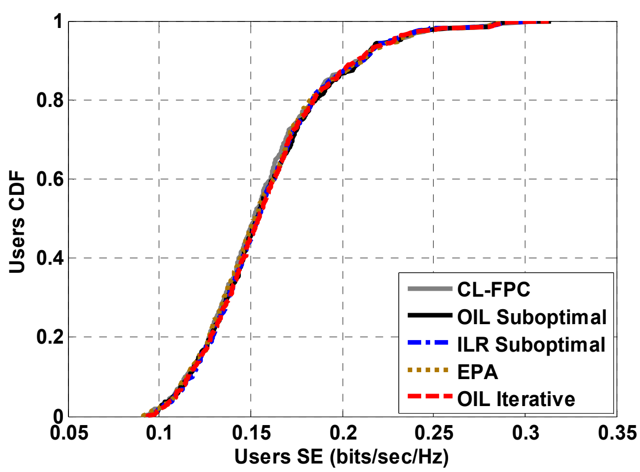

Figure 5: Users CDF at -90 dBm.

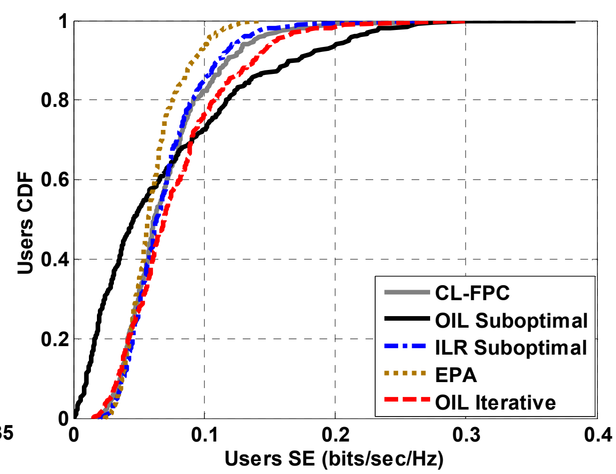

Figure 6: Users CDF at -110 dBm.

6.2 Results of Adaptive ILR Allocation Schemes

Consider the same environment in subsection 6.1 where we apply the adaptive ILR scheme setting the value of $C = 3$ (refer to (16) for significance of C on the interference threshold). Figure 7 and Figure 8 compares the system SE and the 10-percentile throughput of the static ILR scheme with the adaptive heuristic and optimal schemes in the cases when the OI is exchange every 20 ms and with Kalman updates. The adaptive schemes achieve higher SE than the static scheme at low interference limits because the BSs fail the major interferer test more frequently, so they increase their Interference limits. On the other hand, at high interference limits, the adaptive schemes achieve lower SE because BSs tend to tighten their interference limits to alleviate the interference seen by the overloaded BSs.

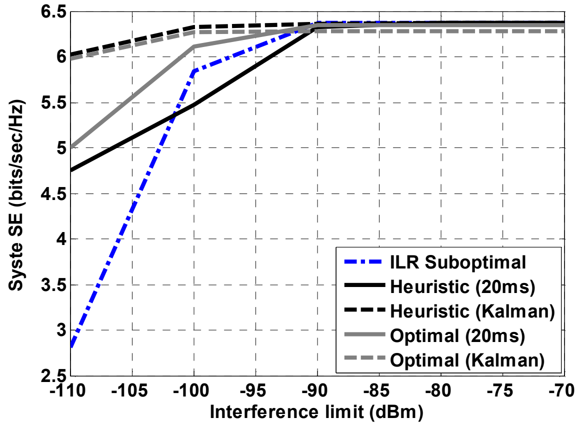

Figure 7: Spectral efficiency of adaptive schemes

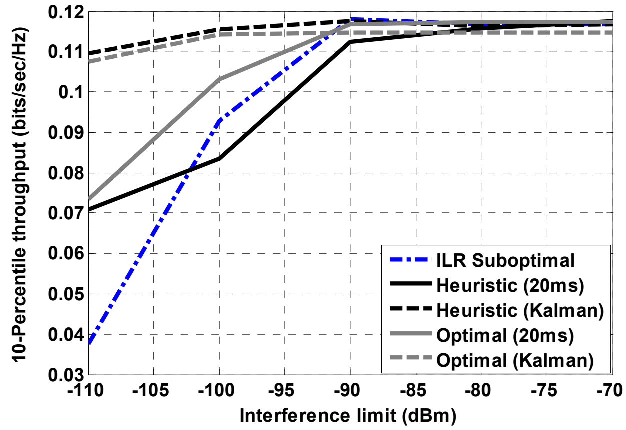

Figure 8: 10-Percentile throughput of adaptive schemes

6.3 Performance of Static Schemes with Random RB Assignment

The above results are generated assuming a proportional fair RB assignment, where each terminal is assigned the best RBs it sees, so the results of the proposed schemes are quite close with the conventional EPA and CL-FPC especially at high interference limits where every terminal is allowed to use its maximum power. However, The SC-FDMA nature of the LTE might not allow each terminal to be assigned its best RBs because they might not be contiguous, so the terminal is more probably to be assigned good and bad RBs. Therefore, in this section we generate the results assuming random RB assignment. Figure 9 and Figure 10 shows the system SE and the 10-percentile throughput of the different schemes. Our proposed schemes exhibits better performance than the conventional schemes because they make use of the channel gain variations over different RBs unlike the equal power allocation nature of the conventional scheme. Also, Figure 11 and Figure 12 show that our schemes provide better rates than the conventional schemes at high and low values of the interference limits.

6.4 Performance of ILR Schemes in Heterogeneous Environment

Consider a HetNet with four Macro BSs located at the vertices of a 1000m×1000m rectangle centred at the origin, and four Pico BSs located at the vertices of a 200m×200m rectangle centred at the origin. Each BS is serving 10 terminals distributed at the cell edge as shown in Figure 13. . Terminals are connected to the BS with maximum downlink received signal strength. The downlink power of a Macro cell is 46 dBm, and the downlink power of a Pico cell is 30 dBm.

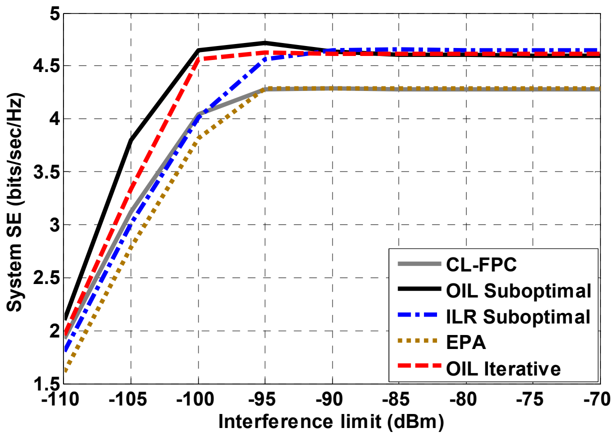

Figure 9: System SE at random RB assignment

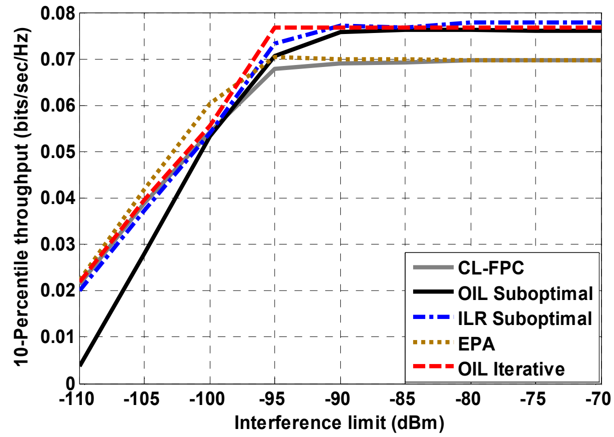

Figure 10: 10-Percentile throughput at random RB assignment

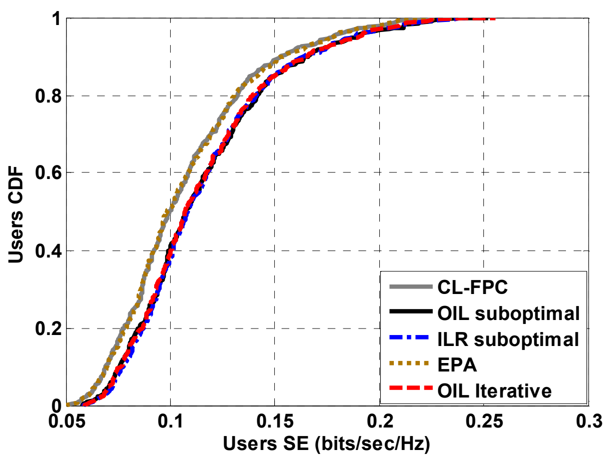

Figure 11: User CDFs at -90 dB with random RB assignment

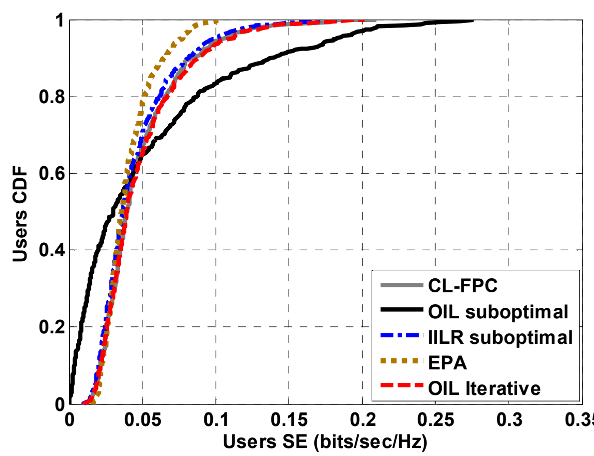

Figure 12: User CDFs at -110 dBm with random RB assignment

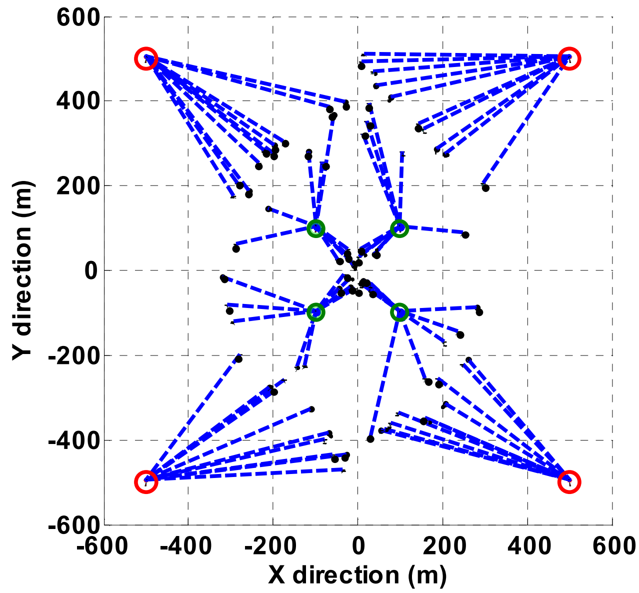

Figure 13: HetNet layout

Figure 14 and Figure 15 and show the effect of changing the system's interference limits on the SE and the 10 percentile throughput of the Macro and the Pico users. Reducing the interference limit of the Pico cells increases the SE and the 10 percentile throughput of the Macro cell users, while reducing those of the Pico cell users, and vice versa. The operator of the HetNet should therefore adapt the limits to the required operating region where total (marco+pico) SE is maximized while the 10-percentile SE is higher than a certain value.

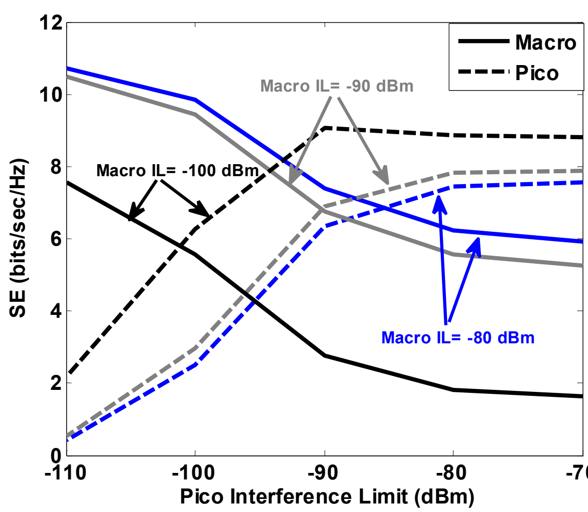

Figure 14: SE of static suboptimal ILR scheme

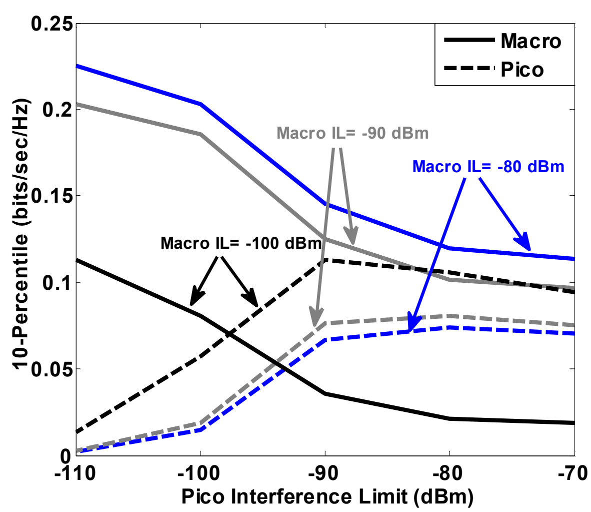

Figure 15: 10 percentile throughput of static suboptimal ILR scheme

Figure 16 shows the effect of changing the system parameters like the SINR threshold that triggers the OI signal, and the constant C defined in (16) on the SE of the Macro and Pico cells starting with IL=-70 dBm for the two tiers. Note that the value of C changes the value of the interference threshold that determines whether the terminal is a major interferer or not. At $= 1$, the interference threshold is high, such that no cell sees itself as a major interferer to any other cell, so the SE is the same overall the SINR thresholds. The picos achieve high SINR because the pico terminals are closer to their serving BSs. At $C = 10$ and $C = 20$, the gap between the SE of the two tiers decreases when the SINR threshold increases. However, the case $C = 20$ imposes a strictly small interference threshold such that the pico cells are identified as major interferer most of the time. Hence they keep reducing their interference limits and hence their SE until it is less than the macros'. This study of the system parameters shows that they should be adjusted according to the environment to achieve fairness among different tiers in a HetNet environment.

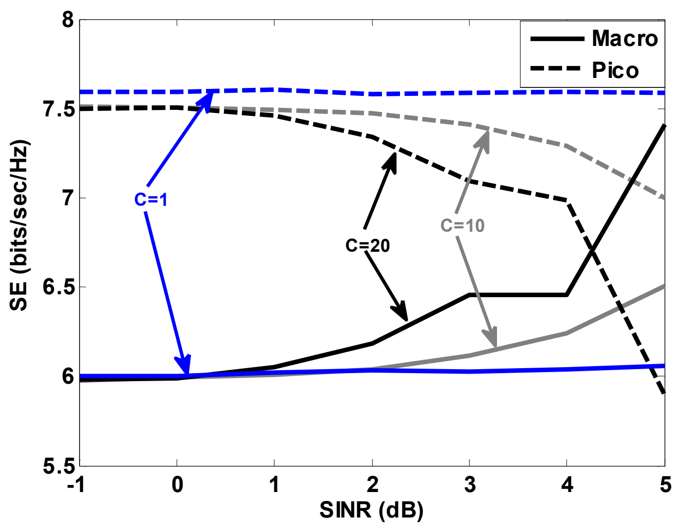

Figure 16: SE of Heuristic Kalman scheme

7 Conclusions and Future Work

This paper presents two frameworks for the autonomous uplink ICIC in OFDMA-based and derivative systems. We propose two autonomous power allocation schemes based on the OIL framework; a closed form suboptimal scheme, and an iterative scheme using Newton's method. We also propose a closed form suboptimal power allocation scheme based on the ILR framework, and we develop two semi-autonomous heuristic and optimal adaptive schemes that use the OI signal in the LTE system to adapt the values of these interference limits of each cell in the suboptimal ILR scheme. To overcome the problem of the slow frequency of the OI exchange between cells, we provide an estimation scheme using the Kalman filter to estimate the values of OIs in the intervals between exchanges.

Simulation results show that the static OIL schemes have better performance than the conventional schemes especially when using random RB assignment as it allows higher channel gain variations over the RBs assigned to the terminal. They also have acceptable performance compared with centralized optimal power allocation given that they require no exchange of information. The static ILR scheme has almost the same performance of the OIL schemes. However, it is advantageous because it can be applied autonomously on a per-terminal basis, and it is easy to update the per-RB interference limits in each cell through the two proposed adaptive schemes which achieve fairness among cells per RB by reducing the interference seen by the overloaded BSs, and they achieve higher SE than the static schemes at low interference limits. Also, simulations show that the adaptive schemes achieve fairness among macro cells and pico cells in a HetNet environment. This fairness can be controlled through changing the scheme parameters like the SINR threshold and the interference threshold. This opens another challenge of how to optimize the system parameters according to the environment and operator requirements.

For extension, we are currently working on evaluating the statistical performance of our work by using stochastic geometry to model this wireless system. We aim at finding a theoretical expression for the probability of coverage in the system when users follow the interference limit paradigm proposed in this work.

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