Autonomous Uplink Intercell Interference Coordination in LTE Systems with Adaptively-tuned Interference Limits

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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. Interference mitigation techniques combat ICI by using proper resource allocation. Centralized allocation is not practical, particularly in heterogeneous networks, as it requires intensive signaling about interference and channel state information that may not always be practically available. This paper presents a framework for autonomous uplink inter-cell interference coordination in OFDMA wireless systems based on imposing an interference limit for each resource block in each cell. This framework gives a suboptimal closed form autonomous power allocation that can be applied autonomously at each terminal. We also propose two semi-autonomous heuristic and optimal adaptive schemes that use the overload indicator signal in LTE to tune the interference limits in order to achieve fairness among cells by alleviating the interference seen by the overloaded cells. Simulations show that the new suboptimal scheme exhibits the same performance as our initial scheme in [1] which imposes an overall interference limit per cell. However, the two main advantages of the new framework are the ability of each terminal to calculate its power independently and that the adaptive interference limit schemes can be applied to adjust the level of interference seen by each cell. Simulations also show that the adaptive schemes achieve fairness among cells by increasing the rates of the overloaded cells at the expense of slightly reducing the rates of the lightly loaded cells.**

Keywords— Complementary Slackness; ICIC; Lagranigian; Overload Indicator; Power Control; Uplink Resource Management.

I. INTRODUCTION

In OFDMA 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). An RB represents the minimum resource 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 attain 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, especially the cell edge users. Interference mitigation techniques attempt to combat ICI by using proper resource allocation schemes. Centralized schemes are not practical, particularly in heterogeneous networks (HetNets), as they require intensive signaling about interference and channel state information that may not always be practically available.

A lot of research work has tackled the problem for downlink inter-cell interference coordination (ICIC) which can be classified as coordinated-distributed, semi-autonomous, and autonomous allocation schemes [2]. However, the uplink ICIC problem has been tackled but less extensively. Yates [3] propose a frame work for uplink power control to mitigate interference using the definition of interference function. Foschini and Miljanic [4] 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. Authors of [5] propose an iterative RB assignment using pairwise coordination between BSs, however the limit to which pairs are grouped is not defined. Each user is assigned the RBs that maximize the total utility gradients of the cell users. The scheme allows/prevents two users in two neighboring cells to use the same RB according to a defined marginal utility function. BSs in [6] exchange interference prices to maximize the weighted sum rates of each cell. The problem of resource allocation is solved iteratively using the Karush-Kuhn-Tucker (KKT) equations or by Newton's method. The authors use the uplink-downlink duality to validate their scheme as a suboptimal scheme for uplink resource allocation. Ref [7] proposes a five-steps-multi-sector-gradient scheme that needs infrequent exchange of interference cost messages between sectors. Each sector maximizes its utility function while considering the degradation that it causes to the utilities of the neighboring sectors. To relax the required accuracy of interference estimation, the algorithm uses the average interference instead of the instantaneous interference. Authors of [8] introduce an autonomous iterative water-filling resource allocation which bounds the egress interference of each BS. They also introduce a constrained noise rise density algorithm, which specifies an egress interference constraint for each RB. This algorithm allows the terminal with maximum weighted rate to transmit on all the RBs with the maximum power that satisfies the interference constraint. In [1], we propose a framework for autonomous uplink ICIC in OFDMA wireless systems. That framework imposes an overall interference limit for each cell. We maximize of the sum of the cell terminals' signal to leakage and noise ratio (SLNR) subject to a threshold to the interference leaked by the cell on its neighbors. We propose a suboptimal closed form allocation, and an iterative allocation using Newton's method.

In this paper, we extend our previous work in [1] by reformulating the autonomous power allocation problem using a different interference limit for each RB instead of an overall interference limit for the whole cell. We derive a closed form suboptimal power allocation using this new problem formulation which can be calculated by each terminal autonomously rather than at the BS. We also propose two semi-autonomous heuristic and optimal adaptive allocation schemes. These adaptive schemes use the overload indicator (OI) signal in the LTE standard [9]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. Simulations show that the new suboptimal interference limit per RB scheme almost achieve the same spectral efficiency as the overall interference limit suboptimal scheme in [1] with the advantages of being autonomous on a per-terminal basis, and being easily adjusted to the network conditions by our two newly proposed adaptive schemes. 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.

II. AUUTONMOUS SUB-OPTIMAL UPLINK POWER ALLOCATION SCHEME

A. *System Model*

Consider an OFDMA-based cellular system consisting of a set of M BSs, 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 long-term (large-scale) channel gain 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.

B. *Problem Formulation*

We consider the same convex autonomous optimization problem in our previous work in [1] as shown in (1) 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.

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

where $G_{s,i} = \sum_{n\in M, n\neq s} g_{n,i}$, and T_s is the overall interference limit. P_{max} is the maximum uplink power allocated per terminal. The first constraint is the total uplink power constraint per terminal, and the second is the overall interference constraint on the interference contributed by all the terminals in BS-s to all other uplink transmissions in the neighboring cells.

In our new formulation in (2), we minimize the same objective in (1) subject to the same first maximum power constraint, but we use different interference constraints for different RBs instead of an overall interference constraint for the whole cell. Each cell in this reformulation 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 given by:

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

The second constraint couples the powers transmitted by all the cell terminals on RB-k which 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:

$$\begin{gathered}\text{Minimize}\\ U_s=-\sum_{i\in I_s}\sum_{k=1}^{K}\frac{p_{i,k}h_{i,k}^{s}\delta_{ik}}{\sigma_{s,k}^{2}+p_{i,k}G_{s,i}}\ \forall s\in M\\ \text{Subject to}\\ \sum_{k=1}^{K}p_{i,k}\delta_{ik}\le P_{max}\ \forall i\in I_s\\ p_{ik}\le\frac{T_{s,k}}{G_{s,i}}\ \ \forall k=1,2,\dots,K,i\in I_s\end{gathered}\tag{3}$$

C. Lagranigan Solution

In this subsection, we write the Lagrangian of the problem in (3) as follows:

$$\begin{aligned}L(\vec{P},\vec{\lambda},\vec{v})&=-\sum_{i=1}^{|I_S|}\sum_{k=1}^{K}\frac{p_{ik}h_{i,k}^{s}\delta_{ik}}{p_{ik}G_{s,i}+\sigma_{s,k}^{2}}+\sum_{i=1}^{|I_S|}\lambda_i\left[\sum_{k=1}^{K}p_{ik}\delta_{ik}-P_{max}\right]\\&+\sum_{k=1}^{K}\sum_{i=1}^{|I_S|}v_{i,k}\delta_{ik}\left[p_{ik}-\frac{T_{s,k}}{G_{s,i}}\right]\\&=\textstyle\sum_{i=1}^{|I_S|}\left[L_i(\vec{P_i},\lambda_i,\vec{v_i})-P_{max}\,\lambda_i\right],\end{aligned}\tag{4}$$

where $L_i(\vec{P_i},\lambda_i,\vec{v_i})$ is the Lagrangian corresponding to terminal-i and λ_i and $\vec{v_i}$ are its Lagrange multipliers.

$$L_i(\vec{P_i},\lambda_i,\vec{v_i})=\sum_{k=1}^{K}\left[-\frac{p_{ik}h_{i,k}^{s}\delta_{ik}}{p_{ik}G_{s,i}+\sigma_{s,k}^{2}}+\delta_{ik}[p_{ik}(\lambda_i+v_{i,k})-\frac{T_{s,k}}{G_{s,i}}v_{i,k}]\right]\tag{5}$$

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} we get:

$$p_{ik}^* = \frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \sqrt{\frac{\sigma_{s,k}^2 h_{i,k}^s}{(\lambda_i^* + v_{ik}^*)}}\right] \tag{6}$$

Solving the complementary slackness conditions iteratively to get the optimal Lagrange multipliers λ_i^* and v_{ik}^* does not give a closed form solution. 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

$$p_{ik}^* = \frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \sqrt{\frac{\sigma_{s,k}^2 h_{i,k}^s}{\lambda_i^*}}\right] \tag{7}$$

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:

$$\sqrt{\lambda_i^*} = \frac{\sum_j \sqrt{\sigma_{s,j}^2 h_{i,j}^s \delta_{ij}}}{G_{s,i} P_{max} + \sum_j \sigma_{s,j}^2 \delta_{ij}} \tag{8}$$

After substituting with λ_i^* in (7), the power allocation becomes

$$p_{ik}^* = \frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \frac{\sqrt{\sigma_{s,k}^2 h_{i,k}^s}\left(G_{s,i} P_{max} + \sum_j \sigma_{s,j}^2 \delta_{ij}\right)}{\sum_j \delta_{ij} \sqrt{\sigma_{s,j}^2 h_{i,j}^s}}\right] \tag{9}$$

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

$$p_{ik}^* = min\left\{\begin{matrix} \frac{1}{G_{s,i}}\left[-\sigma_{s,k}^2 + \frac{\sqrt{\sigma_{s,k}^2 h_{i,k}^s}\left(G_{s,i} P_{max} + \sum_j \sigma_{s,j}^2 \delta_{ij}\right)}{\sum_j \delta_{ij} \sqrt{\sigma_{s,j}^2 h_{i,j}^s}}\right] \\ , \frac{T_{s,k}}{Gs_{,i}} \end{matrix}\right\} \tag{10}$$

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 $G_{s,i}$ 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 (10)) is less than the first argument (calculated power) for terminal-i over all the assigned RBs, 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 which is

$$\frac{(p_{ik} + \Delta) h_{i,k}^s}{\sigma_{s.k}^2 + (p_{ik} + \Delta) G_{s,i}} - \frac{p_{ik} h_{i,k}^s}{\sigma_{s,k}^2 + p_{ik} G_{s,i}} \tag{11}$$

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:

$$k = argmax_j \frac{\Delta h_{i,j}^{s} \sigma_{s,j}^{2}}{(\sigma_{s,j}^{2} + p_{ij} G_{s,i})(\sigma_{s,j}^{2} + (p_{ij} + \Delta) G_{s,i})} \tag{12}$$

If $(p_{ik} + \Delta) > \frac{T_{s,k}}{G_{s,i}}$, we allow the terminal to transmit with maximum power on this RB, and search for the second best RB using (12). We repeat the search and allocation process until there is no extra power remaining or the terminal transmits with the maximum power allowable on all its assigned RBs.

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 scheduling 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.

III. INTERFERENCE LIMIT ADAPTATION

Release 8 LTE and beyond allows the exchange of an OI message between the neighboring BSs over the X2 interface to help acquiring information on interference for proper ICIC [9] . This signal indicates the level of interference (low/medium/high) seen by the BS per RB, and it is exchanged every 20ms. Although the signal is standardized, the action which the neighbors 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 OI message exchange between neighboring 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'

First, each BS assigns the RBs to its terminals using the proportional fair scheme, and every terminal calculates its power using the preceding suboptimal scheme, each BS checks the OI of its neighbors 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 $\frac{p_{max}}{(Num\ of\ neighbors)*K} * mean(G)$, which is the average power leaked by a typical terminal on one of its neighbors if this terminal is assigned all RBs assuming equal power allocation scheme. To calculate the interference threshold, we assume that each terminal-i in BS-s calculates its leakage power density ($G_{s,i}$) through downlink pilots from its neighboring BSs, and reports this value to its serving BS. The BSs then exchange these values and calculate the mean value of the leakage power density of the system terminals ($mean(G)$). The dependence on the large scale parameters to calculate the leakage power and the interference threshold reduces the frequency of channel estimation and the frequency of message exchange between cells. Each BS increases its interference limit on RB-k by 50% if none of its neighbors is overloaded on this RB or if it is not the major interferer on this RB. On the other hand, if it 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 neighbor on the same RB, it considers the BS that receives maximum leakage power from it to be its victim neighbor, and then the adaptive schemes are applied in a pair-wise manner only between the major interfering BS and its victim neighbor. Also to reduce the amount of calculations and message exchange, the major interfering BS does not adapt its power or update its interference limit unless the number of violations of its victim neighbor exceeds the number of its violation on the overloaded RB by at least 25%.

A. Heuristic Adaptive Scheme

In this scheme a further check is made to decide on the action 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 s respectively. Let $h_{i_m,k}^{m}$ and $h_{i_m,k}^{s}$ 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

Algorithm 1: Power update

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If ( $\left|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right| > \frac{\partial R_{s,k}}{\partial p_{s,k}}$ ),
    $p_{s,k} = p_{s,k} * \left|\frac{\partial R_{s,k}}{\partial p_{s,k}}\right| / \left|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right|$
else
    $p_{s,k} = p_{s,k} * \left[1 - \left|\frac{\partial R_{m,k}}{\partial p_{s,k}}\right| / \left|\frac{\partial R_{s,k}}{\partial p_{s,k}}\right|\right]$
end
$T_{s,k} = T_{s,k} - 0.5(p_{s,k} * G_{s,i})$
```

$$\begin{gathered} R_{m,k} = \ln(1 + SINR_{m,k}) \\ SINR_{m,k} = \frac{p_{m,k} h^{m}_{i_m,k}}{\sigma^2_{m,k} + I_{m,k}} \end{gathered} \tag{13}$$

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

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

$U_{m,k} = \frac{1}{1+SINR_{m,k}} . \frac{-p_{m,k} h^{m}_{i_m,k}}{(\sigma^2_{m,k}+I_{m,k})^2}$. The negative sign of $U_{m,k}$ 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. Similarly, we calculate $\frac{\partial R_{s,k}}{\partial p_{s,k}}$ in (14) and the power transmitted by the interfering terminal is updated as shown in Algorithm 1.

$$\begin{gathered} R_{s,k} = \ln(1 + SINR_{s,k}) \\ SINR_{s,k} = \frac{p_{s,k} h^{s}_{i_s,k}}{\sigma^2_{s,k} + I_{s,k}} \\ I_{s,k} = \sum_{n \neq s} p_{n,k} h^{s}_{i_n,k} \\ \frac{\partial R_{s,k}}{\partial p_{s,k}} = \frac{\partial R_{s,k}}{\partial SINR_{s,k}} . \frac{\partial SINR_{s,k}}{\partial p_{s,k}} \\ = \frac{1}{1 + SINR_{s,k}} . \frac{h^{s}_{i_s,k}}{\sigma^2_{s,k} + I_{s,k}} \end{gathered} \tag{14}$$

This heuristic scheme only requires the overloaded BS-m to exchange its $U_{m,k}$ message and the OI with its neighbors. All the other signals that are used in the algorithm can be simply estimated by the major interfering BS-s autonomously through downlink pilots.

B. 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 BSs 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 major interfering BS and its victim neighbor. We maximize the weighed sum of $R_{s,k}$ and $R_{m,k}$ and the weight of the interfering or victim BS is the ratio of the number of violations at the interfering or victim BS to the total number of violations at the two BSs. The problem is given as follows:

$$\begin{gathered}\text{Maximize}\\ w_s R_{s,k}\left(p_{s,k}-\Delta\right)+\ w_m R_{m,k}\left(p_{s,k}-\Delta\right)\\ \text{Subject to}\\ 0\le\Delta\le p_{s,k}\end{gathered}\tag{15}$$

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 $\Delta h_{i_s,k}^{m}$, so the problem in(15) becomes

$$\begin{gathered}\text{Maximize}\\ w_s \ln\left(1+\frac{\left(p_{s,k}-\Delta\right)h_{i_s,k}^{s}}{\sigma_{s,k}^{2}+I_{s,k}}\right)+w_m \ln\left(1+\frac{p_{m,k}h_{i_m,k}^{m}}{\sigma_{m,k}^{2}+I_{m,k}-\Delta h_{i_s,k}^{m}}\right)\\ \text{Subject to}\\ 0\le\Delta\le p_{s,k}\end{gathered}\tag{16}$$

This problem can be solved using DC programing [10] by substituting with the first order approximation of the denominator of the second term in (16) as follows:

$$\begin{gathered}\text{Maximize}\\ w_s f(\Delta)+w_m g_1(\Delta)+w_m g_2(\Delta^j)\ +w_m\frac{\partial g_2(\Delta^j)}{\partial\Delta}(\Delta-\Delta^j)\\ \text{Subject to}\\ 0\le\Delta\le p_{s,k}\end{gathered}\tag{17}$$

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

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

We solve this problem using the FW procedure [10] the power and the interference limit are updated as follows

$$p_{s,k}=p_{s,k}-\Delta,\quad T_{s,k}=T_{s,k}-0.5\left[p_{s,k}*G_{s,i}\right]$$

IV. PERFORMANCE EVALUATION

Consider an OFDMA network of four macro BSs located at the vertices of a 1000m×1000m square area centered at the origin, and twenty terminals are uniformly distributed over a 250m × 250m square area centered at the origin and each terminal is served by the nearest BS. Each terminal and BS has a single Omni-directional antenna. The total number of RBs is 15, 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. In our simulation, we assume that the OI is exchanged every 1ms, however this is not an obligatory assumption as the adaptive schemes can be applied every 20ms instead of 1ms. Also every BS can estimate the values of the OI using any simple estimation method like the Kalman filter.

Fig. 1 shows the spectral efficiency of our new suboptimal scheme (interference limit per RB without OI adaptation) and the previously proposed suboptimal power allocation (overall interference limit) in [1]. The two schemes have close performance especially at high values of interference limits ($-90\colon -70$ dBm), while the per RB scheme exhibits lower spectral efficiency at small values of interference limit. This behavior 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 per RB scheme. This comes by rewriting the interference constraint in (1) as follows:

$$\sum_{k=1}^{K}\sum_{i\in I_s} p_{i,k}G_{s,i} \le \sum_{k=1}^{K} T_{s,k}$$

Since each RB-k is assigned to one terminal only (i_k) in the cell, then the constraint can be further simplified to:

$$\sum_{k=1}^{K} p_{i_k,k}G_{s,i_k} \le \sum_{k=1}^{K} T_{s,k}$$

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. The figure also shows that the spectral efficiency of the heuristic adaptive scheme is the same as the highest spectral efficiency achieved by the two suboptimal schemes. Fig. 1 also shows that the optimal and the heuristic adaptive schemes outperform the two suboptimal schemes at small interference limits.

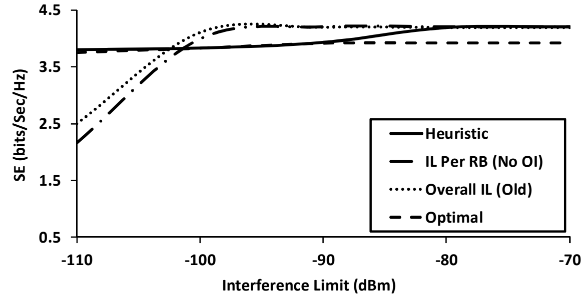

Figure 1: System spectral efficiency (SE)

Fig. 2 to Fig. 4 show the violations of the 4 cells over every RB using the per-RB interference limit suboptimal scheme and the two adaptive schemes at -70 dBm interference limit. The violations represent how many times the BS was overloaded on specific RB. An overload occurs when SINR on a RB is less than a threshold taken as 0 dB in the simulations. The figures show that adaptive algorithms (particularly the optimal scheme) reduce the number of violations of the overloaded BSs while slightly increasing the number of violations of the lightly loaded cells. The adaptive schemes allow all the BSs to achieve good rates on the same RB.

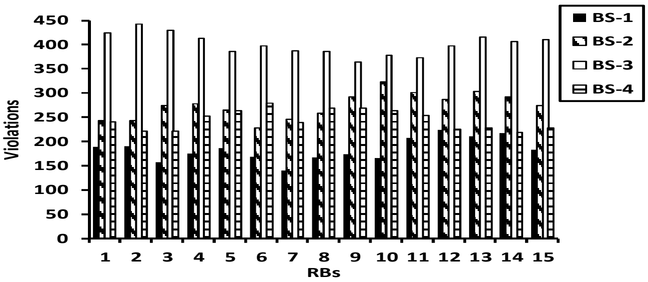

Figure 2: Violations over RBs (no OI exchange)

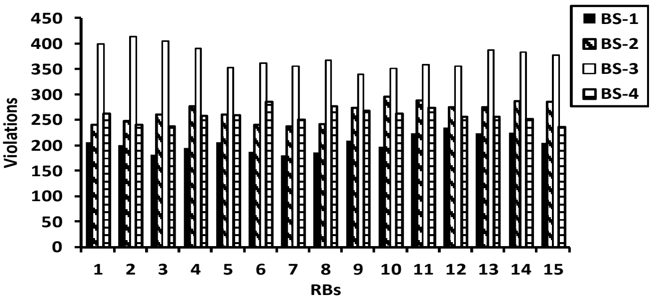

Figure 3: Violations over RBs (heuristic adaptive scheme)

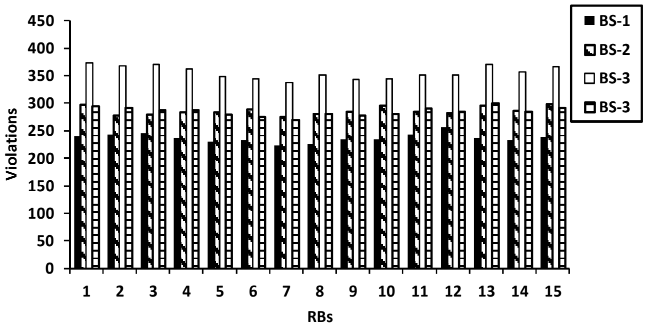

Figure 4: Violations over RBs (optimal adaptive scheme)

Fig. 5 shows that BS-3 has bad rates on RB-2 so it has many violations. The adaptive schemes improve the CDF of this BS by getting the other lightly loaded BSs to lower their transmission power to enable the overloaded BS to improve its rates on that RB. Fig. 7 shows that the optimal scheme enables the overloaded BSs to have better rates than the heuristic algorithm in Fig. 6 as it considers the both the violations and the system utility.

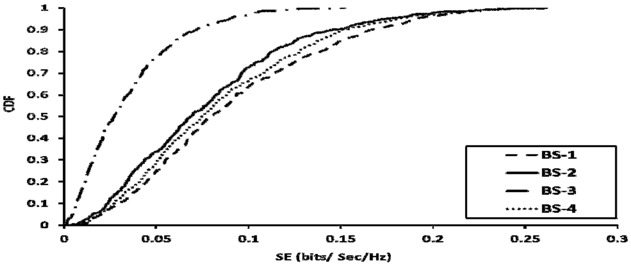

Figure 5: SE CDFs over RB-2 (no OI exchange)

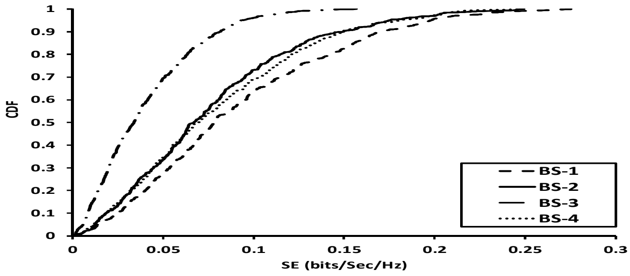

Figure 6: SE CDFs over RB-2 (heuristic adaptive scheme)

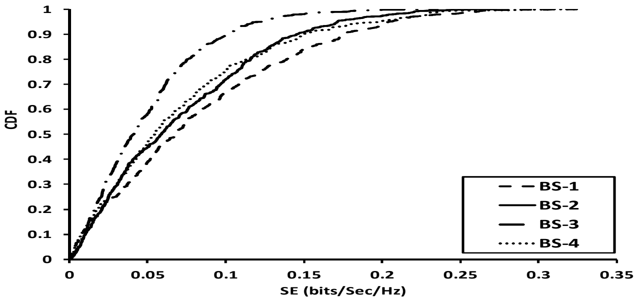

Figure 7: SE CDFs over RB-2 (optimal adaptive scheme)

Fig. 8 shows the CDF of the sum rates of the four BSs on RB-2 for the three proposed schemes at −70 dBm interference limit. It shows that the case of no OI exchange the system achieves higher sum rates on RB-2, however this comes at the expense of the rates achieved by the overloaded BSs. The heuristic adaptive scheme reduces the power of a major interferer with a heuristic step. Although it does not reduce the sum rates the violations seen by the overloaded BSs are still high. On the other hand, the optimal adaptive scheme calculates the optimum step that maximizes the weighted sum rates of the overloaded BS and the major interferer. Since it considers the percentage of time over which each BS is overloaded, it sacrifices the high rates of the lightly loaded BSs to reduce the violations seen by the overloaded BSs, and this explains why the sum rates CDF curve on RB-2 of the optimal adaptive scheme is slightly worse than the other two curves, and this explains its lower SE in Fig. 1.

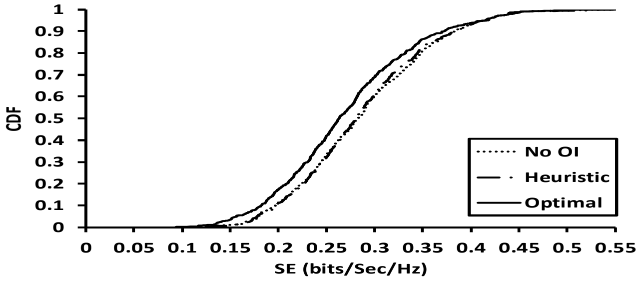

Figure 8: Total SE CDFs on RB-2

V. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced a frame work for a per-terminal autonomous power allocation to combat the ICI in an OFDMA-based system. We imposed a different interference limit to every RB in the cell, and obtained a closed-form solution for the power allocation on each RB. We also developed two semi-autonomous heuristic and optimal adaptive schemes that use the OI signal in the LTE to tune the values of these interference limits in each cell. In our future work, we use the Kalman filter to estimate the values of the OI in order to study the effect of the frequency of the OI exchange on the system performance. We also study the effect of changing the scheme parameters such as the interference threshold and the SINR threshold that triggers the OI on the system performance and evaluate the performance of our schemes when applied in HetNets. The contiguity of the RB assignment in the LTE uplink might encourage to adopt the idea of clustering RBs such that our proposed schemes are applied on a per cluster basis rather than on a per RB basis in order to reduce the amount of overhead in case of large number of RBs.

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