Neighbor-friendly user scheduling algorithm for interference management in LTE-A networks

Rodolfo Torrea-Duran[1], Luc Vandendorpe[2], and Marc Moonen[1]
[1]KU Leuven, Department of Electrical Engineering (ESAT)
STADIUS Center for Dynamical Systems, Signal Processing and Data Analytics, Leuven, Belgium
[2]Université Catholique de Louvain, ICTEAM Institute, Digital Communications Group, LLN, Belgium
{Rodolfo.TorreaDuran, Marc.Moonen}@esat.kuleuven.be, Luc.Vandendorpe@uclouvain.be

***Abstract*—Downlink inter-cell interference is considered as a major challenge for cellular systems. For this purpose, the Long Term Evolution Advanced (LTE-A) standard uses soft frequency reuse (SFR), which assigns two fixed disjoint portions of the available bandwidth, one for center users and one for cell edge users. However, SFR forces the allocation of users in a certain portion of the bandwidth regardless of the users' channel conditions. Neighbor-friendly power control techniques have been studied as a means to reduce inter-cell interference in neighboring cells without forcing users to a certain bandwidth portion. Nevertheless, they are not directly applicable to LTE-A since the granularity of the power levels and the exchange of information between base stations are limited. In this paper, we use the principles of neighbor-friendly power control to develop a user scheduling algorithm that assigns physical resource blocks (PRBs) to users based on the channel quality indicator (CQI) and uses relative narrowband transmit power (RNTP) signalling to reallocate users whenever inter-cell interference is detected. Compared to the baseline algorithms, the proposed algorithm is able to increase the instantaneous CQI efficiency especially of cell edge users.**

***Index Terms*—CQI, inter-cell interference, power control**

I. Introduction

Downlink inter-cell interference is a major challenge for cellular networks designed to operate with a frequency reuse factor of 1 [1], [2]. For this purpose, the Long Term Evolution Advanced (LTE-A) standard [3] uses soft frequency reuse (SFR) in which the total bandwidth in every base station is shared by the center users, while a fixed disjoint portion is reserved to cell edge users prone to high inter-cell interference [4]. A coarse power control is then applied by allocating a higher transmit power level to cell edge users to compensate for the larger path loss. However, SFR forces the allocation of center and cell edge users to a certain portion of the bandwidth regardless of their channel conditions.

This research work was carried out at the ESAT Laboratory of KU Leuven, in the frame of KU Leuven Research Council PFV/10/002 (OPTEC), FWO project G091213N "Cross-layer optimization with real-time adaptive dynamic spectrum management for fourth generation broadband access networks", and the Belgian Programme on Interuniversity Attraction Poles initiated by the Belgian Federal Science Policy Office: IUAP "Belgian network on stochastic modelling, analysis, design and optimization of communication systems (BESTCOM)" 2012-2017. The first author acknowledges the support of the Mexican National Council for Science and Technology (CONACYT). The scientific responsibility is assumed by its authors.

978-1-4673-6540-6/15/$31.00 © 2015 IEEE

Center and cell edge users can be classified according to the channel quality indicator (CQI) they feed back to the base station. This value is computed for the whole bandwidth or per physical resource block (PRB), as assumed in this paper, which is the minimal resource allocation unit in LTE-A corresponding to 12 consecutive subcarriers over one time-slot. Based on reference signals transmitted by each base station, the users can compute their CQI as the index corresponding to the highest modulation and coding transmission scheme supporting a block error rate not exceeding 10%. The CQI is thus a measure of both the signal-to-interference-and-noise ratio and the receiver capabilities in a certain PRB [4]. Therefore, for simplicity, we refer to cell edge users as those reporting a low CQI and center users as those reporting a high CQI. Although the CQI feedback procedure is standardized, the selection of which users to schedule in each PRB is the manufacturer's choice of implementation and it is done at each base station independently.

Neighbor-friendly downlink power control techniques have been studied as a means to reduce inter-cell interference in neighboring cells without forcing users to a certain bandwidth portion. Similarly, in the DSL context, a set of power allocation algorithms based on iterative water-filling (IWF) [5] has been proposed in [6] and [7] introducing the concept of protection of a reference user suffering interference from a contiguous transmission. In [8], [9] this neighbor-friendly approach has been used in cellular networks to protect users from neighboring cells. However, these techniques are not directly applicable to LTE-A since since the granularity of the power levels and the exchange of detailed channel and interference information between base stations are limited [10]. Despite these limitations, LTE-A offers some degree of interference coordination by allowing direct exchange of some interference information between neighboring base stations through the X2 interface [11].

In this paper, we use the principles of neighbor-friendly power control to protect the data rate of users from neighboring cells in a LTE-A network. Specifically, we propose a user scheduling algorithm that does not restrict center and cell edge users to a certain portion of the bandwidth. The proposed scheduling algorithm uses CQIs for PRB assignment and RNTP signalling to exchange interference information between neighboring base stations in order to reduce inter-

cell interference. Compared to the baseline algorithms, the proposed algorithm is able to increase the instantaneous CQI efficiency especially of cell edge users.

The paper is organized as follows. Section II describes the neighbor-friendly power control. Section III presents the proposed user scheduling algorithm. Section IV presents the performance evaluation. Finally section V draws some conclusions.

II. Neighbor-friendly power control

Consider a cellular network composed of two neighboring base stations sharing the total available bandwidth[1]. As in LTE-A, we assume orthogonal frequency division multiplexing (OFDM) as multi-carrier transmission scheme. This means that users within a cell are assigned a disjoint set of subcarriers, but users from neighboring cells can share subcarriers hence producing inter-cell interference. We start our analysis on a per-subcarrier basis and then extend it to a PRB-basis. We consider a downlink transmission over K subcarriers and L users connected to each base station.

The goal of each base station is to maximize the data rate of the users connected to it, which can be expressed as the following optimization problem:

$$\begin{aligned} \underset{p_k^b\ \forall k}{\text{maximize}} \quad & \sum_{i=1}^{L} R^{i,b} \\ \text{s.t.} \quad & \sum_{k=1}^{K} p_k^b \leq P^{b,\text{tot}} \\ & 0 \leq p_k^b \leq p_k^{b,\text{mask}}\ \forall k \end{aligned} \tag{1}$$

with

$$\begin{aligned} R^{i,b} &= f_s \sum_{k=1}^{K} \delta_k^{i,b} \log_2 \left(1 + \frac{|h_k^{i,b}|^2 p_k^b}{|h_k^{i,\bar{b}}|^2 p_k^{\bar{b}} + \sigma_k^i}\right) \\ &= f_s \sum_{k=1}^{K} \delta_k^{i,b} \log_2 \left(1 + \frac{S_k^i}{I_k^{i,b} + \sigma_k^i}\right), \end{aligned} \tag{2}$$

where $R^{i,b}$ is the data rate of user i connected to base station b and $\delta_k^{i,b} = 1$ if subcarrier k is allocated to user i and $\delta_k^{i,b} = 0$ otherwise. The parameter f_s is the symbol rate, σ_k^i, p_k^b, $p_k^{\bar{b}}$, and $p_k^{b,\text{mask}}$ are the noise power received by user i, the transmit power of base station b and base station $\bar{b}$, and the spectral emission mask constraints of base station b on subcarrier k, respectively; h_k^b and $h_k^{\bar{b}}$ are the channel gains from base station b and base station $\bar{b}$ to user i on subcarrier k. The parameters $S_k^{i,b}$ and $I_k^{i,b}$ are the received signal and the interference of user i on subcarrier k, hence $\frac{S_k^{i,b}}{I_k^{i,b}+\sigma_k^i}$ represents the signal-to-interference-and-noise ratio of user i on subcarrier k, i.e. SINR_k^i. The parameter $P^{b,\text{tot}}$ is the total power budget in base station b. The two constraints in problem (1) refer to the total power constraint and the spectral emission mask constraint per subcarrier.

[1]Here we analyze the case of only one strongly interfering neighboring base station. However, a similar analysis could be performed for any number of neighboring base stations.

Using the corresponding Karush-Kuhn-Tucker (KKT) conditions, it can be shown that the optimal transmit powers follow a closed-form solution:

$$p_k^b = \left[\frac{f_s}{\log(2)\lambda} - \frac{I_k^{i,b} + \sigma_k^i}{|h_k^{i,b}|^2}\right]_0^{p_k^{b,\text{mask}}}, \tag{3}$$

where $[x]_a^b = \max(a, \min(x, b))$ and λ is the Lagrange multiplier that has to be adjusted (e.g. with bisection) to satisfy the total power constraint $P^{b,\text{tot}}$.

Solution (3), when iteratively applied in each base station, is known as iterative waterfilling (IWF) [5] and it provides the optimal power allocation in a greedy fashion. However, the greediness of one base station affects the neighboring base station since increasing the transmit power also increases the interference received by the users connected to the neighboring base station, especially those at the cell edge.

To avoid this, the neighbor-friendly power control considers the weighted sum-rate maximization of the data rates of users from both base stations:

$$\begin{aligned} \underset{p_k^b\ \forall k}{\text{maximize}} \quad & W^b \sum_{i=1}^{L} R^{i,b} + W^{\bar{b}} \sum_{j=1}^{L} R^{j,\bar{b}} \\ \text{s.t.} \quad & \sum_{k=1}^{K} p_k^b \leq P^{b,\text{tot}} \\ & 0 \leq p_k^b \leq p_k^{b,\text{mask}}\ \forall k \end{aligned} \tag{4}$$

where $R^{j,\bar{b}}$ refers to the data rate of user j connected to base station $\bar{b}$ and can be expanded as

$$\begin{aligned} R^{j,\bar{b}} &= f_s \sum_{k=1}^{K} \delta_k^{j,\bar{b}} \log_2 \left(1 + \frac{|h_k^{j,\bar{b}}|^2 p_k^{\bar{b}}}{|h_k^{j,b}|^2 p_k^b + \sigma_k^j}\right) \\ &= f_s \sum_{k=1}^{K} \delta_k^{j,\bar{b}} \log_2 \left(1 + \frac{S_k^{j,\bar{b}}}{I_k^{j,\bar{b}} + \sigma_k^j}\right), \end{aligned} \tag{5}$$

where $\delta_k^{j,\bar{b}} = 1$ if subcarrier k is allocated to user j and $\delta_k^{j,\bar{b}} = 0$ otherwise. The parameters $S_k^{j,\bar{b}}$ and $I_k^{j,\bar{b}}$ are the received signal and the interference of user j on subcarrier k, hence $\frac{S_k^{j,\bar{b}}}{I_k^{j,\bar{b}}+\sigma_k^j}$ represents the signal-to-interference-and-noise ratio of user j on subcarrier k, i.e. SINR_k^j. The parameters W^b and $W^{\bar{b}}$ represent the weights (priorities) assigned to the users of base stations b and $\bar{b}$. [2]

Applying the KKT stationarity condition to problem (4) on a per-subcarrier basis leads to

$$\frac{\frac{1}{\log(2)} W^b f_s |h_k^{i,b}|^2}{\left(S_k^{i,b} + I_k^{i,b} + \sigma_k^i\right)} - \frac{\frac{1}{\log(2)} W^{\bar{b}} f_s S_k^{j,\bar{b}} |h_k^{j,b}|^2}{\left(I_k^{j,\bar{b}} + \sigma_k^j\right)\left(S_k^{j,\bar{b}} + I_k^{j,\bar{b}} + \sigma_k^j\right)} - \lambda = 0, \tag{6}$$

where λ is the Lagrange multiplier that has to be adjusted (e.g. with bisection) to satisfy the total power constraint

[2]Different weights can be assigned to individual users. However, here we restrict ourselves to the case where the same weight is assigned to all the users of one base station.

$P^{b,\text{tot}}$. Then, by taking into account the KKT complementarity conditions, p_k^b can be computed as:

$$p_k^b = \left[\frac{W^b \frac{f_s}{\log(2)}}{\lambda + T_k} - \frac{I_k^{i,b} + \sigma_k^i}{|h_k^{i,b}|^2} \right]_0^{p_k^{b,\text{mask}}}, \quad (7)$$

where T_k is the penalty factor that reduces the interference caused by base station b to users connected to base station $\bar{b}$. It is defined as

$$\begin{aligned} T_k &= \frac{W^{\bar{b}} f_s S_k^{j,\bar{b}} |h_k^{j,b}|^2}{\log(2) \left(I_k^{j,\bar{b}} + \sigma_k^j \right) \left(I_k^{j,\bar{b}} + S_k^{j,\bar{b}} + \sigma_k^j \right)} \\ &= \frac{W^{\bar{b}} f_s |h_k^{j,b}|^2}{\log(2) \left(I_k^{j,\bar{b}} + S_k^{j,\bar{b}} + \sigma_k^j \right)} \text{SINR}_k^j. \end{aligned} \quad (8)$$

Setting T_k to zero will result in IWF. The sum-rate maximization problem (4) is a nonconvex optimization problem for which a duality gap exists between the solution of (7) and the optimal solution. However, as the number of subcarriers increases, this duality gap goes to zero [12].

From equation (8), we can observe that a high SINR_k^j decreases the power allocation p_k^b as a way to protect the data rate of users from base station $\bar{b}$.

Assuming $W^b = 1 - W^{\bar{b}}$ and varying the value of $W^{\bar{b}}$ from zero to one, we can generate a rate region that trades off the data rates of both cells as seen in Fig. 1. Since IWF cannot provide this trade-off, the total power is typically tuned between 0 and $P^{b,\text{tot}}$ to obtain different operating points. With high inter-cell interference, IWF achieves only a poor performance, while the neighbor-friendly power control achieves a larger rate region for all operating points. This result highlights the importance of providing some level of protection to users in cell $\bar{b}$.

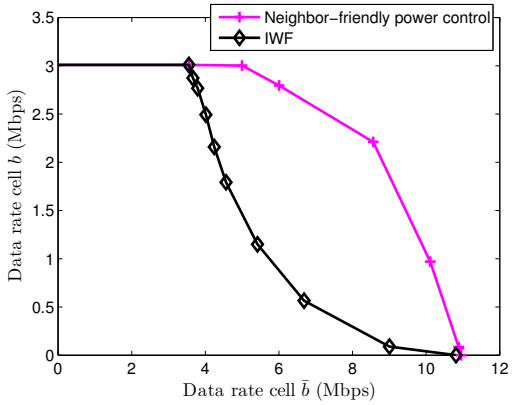

Fig. 1. Rate region for 2 neighboring cells with parameters from Table I averaged over multiple channel realizations.

III. Proposed User Scheduling Algorithm

Given its per-subcarrier granularity and continuous power values, the neighbor-friendly power control is not directly applicable to LTE-A. Also, the computation of the penalty factor from equation (8) requires per-subcarrier knowledge of the channel, the received signal, and the interference of users from base station $\bar{b}$. Furthermore, this information might vary drastically within a few time-slots, reducing the accuracy at the time power control is performed.

Parameter	**Value**
System Bandwidth	5 MHz
Number of subcarriers K	200
Number of users per base station L	10
f_s	1.4 Gsymbols/s
Channel profile	SCM suburban macro [13]
Base station total transmit power $P^{b,\text{tot}}$	50dBm
Mask constraint per subcarrier $p_k^{b,\text{mask}}$	50dBm

TABLE I
Simulation parameters.

For this purpose, LTE-A has designed a system for downlink interference coordination that reduces this information overhead. This is done through the relative narrowband transmit power (RNTP) map, which can be directly exchanged between base stations through the X2 interface, without passing through the core network [10]. Each bit of this map corresponds to one PRB and it indicates whether a base station is planning to keep the transmit power in a PRB larger than a predefined threshold [11]. The value of this threshold as well as the time period for which the RNTP is valid are configurable [10].

The neighbor-friendly power control shows us how the power allocation of both base stations are coupled: increasing the transmit power of one base station increases the interference caused to the users connected to the other and vice versa. For this purpose, we propose a user scheduling algorithm that reduces the inter-cell interference level using LTE-A-compliant signalling. It consists of two steps. First, a proportional fairness user scheduling is performed based on the CQI values reported by each user. Second, a RNTP-based reallocation of cell edge users is performed whenever the same PRB is assigned to two cell edge users of different neighboring cells.

A. CQI-based proportional fairness user scheduling

The proposed CQI-based proportional fairness user scheduling algorithm consists in each base station assigning PRB m in time-slot t to the user with the highest ratio between the instantaneous and the average CQI efficiency:

$$i_m^*(t) = \arg\max_i \frac{\epsilon_m^i(t)}{\text{E}^i(t-1)}, \quad (9)$$

where $\epsilon_m^i(t)$ is the instantaneous CQI efficiency of user i in PRB m in time-slot t, i.e. the information bits that user i would have in time-slot t if allocated PRB m with the latest fed back CQI. The parameter $\text{E}^i(t-1)$ is the average CQI efficiency, i.e. the average information bits that user i has received until time-slot $t-1$. Both of the parameters can be obtained from Table II taken from the LTE standard [10]. The CQI-based proportional fairness user scheduling is summarized in Algorithm 1.

Algorithm 1 CQI-based proportional fairness user scheduling

For each base station:
for $m = 1 : M$ **do**
  for $i = 1 : L$ **do**
    Compute $\epsilon_m^i(t)$ and $\mathrm{E}^i(t-1)$ using Table II
    Assign PRB m to user $i_m^*(t)$ according to equation (9). A higher power level is assigned to cell edge users.
  end for
end for

CQI	Modulation	Coding Rate	CQI Efficiency
0	No transmission	No transmission	No transmission
1	QPSK	0.0762	0.1524
2	QPSK	0.1172	0.2344
3	QPSK	0.1885	0.3770
4	QPSK	0.3008	0.6016
5	QPSK	0.4385	0.8770
6	QPSK	0.5879	1.1758
7	16QAM	0.3691	1.4764
8	16QAM	0.4785	1.9140
9	16QAM	0.6016	2.4064
10	64QAM	0.4551	2.7306
11	64QAM	0.5537	3.3222
12	64QAM	0.6504	3.9024
13	64QAM	0.7539	4.5234
14	64QAM	0.8525	5.1150
15	64QAM	0.9258	5.5548

TABLE II
INSTANTANEOUS CQI EFFICIENCY.

From equation (9), it can be seen that each PRB can be allocated to a center or to a cell edge user. Hence users are not forced to a certain bandwidth portion, while still keeping different power levels. Also, the availability of the CQI values of each user at the base station makes Algorithm 1 straightforward to implement.

B. RNTP-based interference management

Once the CQI-based proportional fairness user scheduling is performed, each base station derives a RNTP map $\mathcal{A}^b = \{a_1^b, a_2^b, ...a_M^b\}$, where a_m^b is the control bit corresponding to PRB m in base station b and M is the total number of PRBs. A one is assigned to a PRB with an instantaneous CQI efficiency lower than threshold τ^b (cell edge user), and a zero otherwise (center user), i.e. $a_m = 1$ if $e_m^{i*(t)}(t) < \tau^b$ and $a_m = 0$ otherwise. This threshold can be seen as the weight (priority) W^b defined in section II and it can be determined based on the average CQI efficiency $\mathrm{E}^i(t-1)$ of the cell edge users. For example, when the average CQI efficiency is low, a high threshold is set to give a larger priority to the cell edge users.

The RNTP map and the threshold are then shared between neighboring base stations. Each base station compares it with its own RNTP map. If there is a one in the same PRB of both RNTP maps, it means that both base stations are assigning a cell edge user on the same PRB. We propose then that only the base station with the highest priority keeps this PRB, while the base station with lowest priority reallocates the PRB to the center user with the highest CQI value. If both base stations have the same priority, both reallocate the PRB to the center user with the highest CQI value. This guarantees that most users keep the assigned PRBs, while only a few users of the low priority base station are reallocated to avoid inter-cell interference. The RNTP-based interference management is summarized in Algorithm 2.

Algorithm 2 RNTP-based interference management

For each base station:
Initialize τ^b according to the average CQI efficiency $\mathrm{E}^i(t-1)$ of cell edge users.
for $m = 1 : M$ **do**
  if $\epsilon_m^i(t) < \tau^b$ **then**
    $a_m^b = 1$
  else
    $a_m^b = 0$
  end if
end for
Share the threshold τ^b and RNTP bit map $\mathcal{A}^b$ with the neighboring base stations through the X2 interface.
for $m = 1 : M$ **do**
  if $a_m^b = a_{m_}^{\bar{b}} = 1$ **then**
    if $\tau^b > \tau^{\bar{b}}$ **then**
      Keep PRB m to the assigned cell edge user.
    else
      Reallocate in PRB m to the center user with the highest CQI value.
    end if
  end if
end for

IV. PERFORMANCE EVALUATION

We classify users as center users if they have a CQI efficiency larger than or equal to the threshold τ^b and as cell edge users if they have a CQI efficiency lower than the threshold τ^b. We assume that the probability distribution of CQI values in each PRB is uniform from 0 to 15. We analyze only the case where $\tau^b = \tau^{\bar{b}}$ leaving the case where $\tau^b \neq \tau^{\bar{b}}$ for future work.

We compare the proposed algorithm with two baseline algorithms. The CQI-based proportional fairness user scheduling of section III-A is performed in both baseline algorithms, but the interference management part is different for each of them.

The first baseline algorithm is SFR, which assigns a disjoint portion of the bandwidth to center and cell edge users in order to avoid inter-cell interference. We fix a bandwidth ratio of 1/3 to the cell edge users, and 2/3 to the center users. If the CQI-based user scheduling allocates a PRB to a cell edge user in the center user bandwidth portion, SFR reallocates the PRB to the center user with the highest CQI value. A similar situation

happens if a PRB is allocated to a center user in the cell edge user bandwidth portion.

The second baseline algorithm is referred to as *Interference*. It corresponds to the case in which we assign users corresponding to the CQI-based user scheduling, but we do not reallocate PRBs in case of inter-cell interference as in section III-B. Therefore, if two cell edge users from neighboring base stations are assigned the same PRB, the interference will lead to both of them losing their transmission, dropping the CQI level to zero.

Fig. 2 shows the cumulative distribution function (CDF) of the center users for $\tau^b = 5$ and $\tau^b = 10$. The number of points corresponds to each of the CQI discrete values. We can observe that there is little difference in the instantaneous CQI efficiency of the center users for the three algorithms. SFR does not depend on τ^b since the ratio of cell edge to center users is always the same. The performance of *Interference* and the proposed algorithm are the same for center users since none of the two algorithms forces users to a certain portion of the bandwidth.

As for the instantaneous CQI efficiency of the cell edge users, the difference between the three algorithms is more evident as seen in Fig. 3. SFR has still the worst performance because of the forced allocation of users. Interestingly, the difference between *Interference* and the proposed algorithm increases with τ^b for the case of cell edge users. This is because the proposed algorithm avoids inter-cell interference by reallocating users according to the RNTP bit map. Also, a larger τ^b gives a larger priority to cell edge users, hence increasing the instantaneous CQI efficiency of the proposed approach.

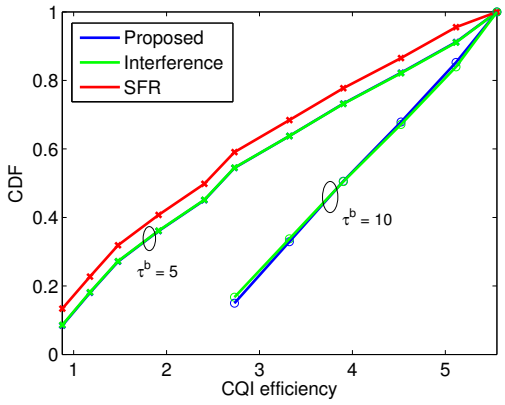

Fig. 2. CDF of the instantaneous CQI efficiency of center users.

V. Conclusions

In this paper we have used the principles of neighbor-friendly power control to develop a user scheduling algorithm that assigns PRBs to users based on CQI-based proportional fairness. Then, it uses RNTP signalling to exchange interference information among base stations and it reallocates users whenever inter-cell interference is detected. Compared to the baseline algorithms, the proposed algorithm is able to increase the instantaneous CQI efficiency especially of cell edge users without degrading the performance of center users.

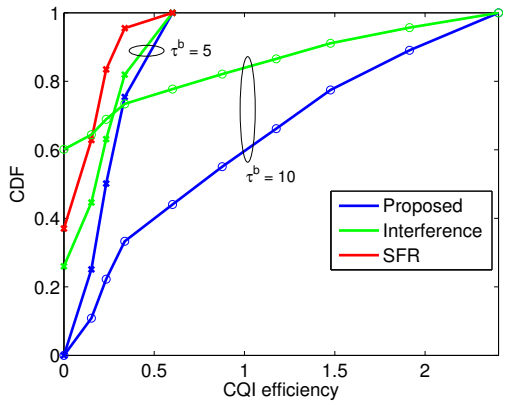

Fig. 3. CDF of the instantaneous CQI efficiency of cell edge users.

References

[1] C. Kosta, B. Hunt, A. UI Quddus, and R. Tafazolli, "On interference avoidance through inter-cell interference coordination (ICIC) based on OFDMA mobile systems", *IEEE Comms. Surveys & Tutorials*, pp. 1-23, 2013.

[2] D. Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T. Q. S. Quek, and J. Zhang, "Enhanced inter-cell interference coordination challenges in heterogeneous networks", *IEEE Wireless Comms.*, vol.18, no.3, pp.22-30, Jun 2011.

[3] 3rd Generation Partnership Project, "Overall description", *Technical Specification Group Radio Access Network*, TS 36.300, Stage 2, Release 12, v.12.4.0, Dec. 2014.

[4] S. Sesia, I. Toufik, and M. Baker, "LTE - the UMTS Long Term Evolution: from theory to practice", *John Wiley and Sons*, 2009.

[5] W. Yu, G. Ginis, and J. Cioffi, "Distributed multiuser power control for digital subscriber lines", *IEEE Trans. on Sel. Areas in Comms.*, vol. 20, no. 5, Jun. 2002.

[6] R. Cendrillon, J. Huang, M. Chiang, and M. Moonen, "Autonomous Spectrum Balancing for Digital Subscriber Lines", *IEEE Trans. on Signal Processing*, vol. 55, no. 8, Oct. 2007.

[7] P. Tsiaflakis, M. Diehl, and M. Moonen, "Distributed spectrum management algorithms for multiuser DSL networks", *IEEE Trans. on Signal Processing*, vol. 56, no. 2, Oct. 2008.

[8] K. Son, S. Lee, Y. Yi, and S. Chong, "REFIM: A practical interference management in heterogeneous wireless access networks", *IEEE Trans. on Sel. Areas in Comms.*, vol. 29, no. 6, Aug. 2011.

[9] R. Torrea-Duran, P. Tsiaflakis, M. Moonen, and L. Vandendorpe, "Neighbor-Friendly Autonomous Power Control in Wireless Heterogeneous Networks", *EURASIP Journal on Wireless Communications and Networking*, Oct. 2014.

[10] 3rd Generation Partnership Project, "Physical layer procedures", *Technical Specification Group Radio Access Network*, TS 36.213, Release 12, v12.4.0, Dec. 2014.

[11] 3rd Generation Partnership Project, "X2 application protocol", *Technical Specification Group Radio Access Network*, TS 36.423, Release 12, v12.4.2, Dec. 2014.

[12] R. Cendrillon, W. Yu, M. Moonen, J. Verlinden, and T. Bostoen, "Optimal multiuser spectrum balancing for digital subscriber lines", *IEEE Trans. on Comms.*, vol. 54, no. 5, May. 2006.

[13] 3GPP, "Spatial channel model for Multiple Input Multiple Output (MIMO) simulations", TR 25.996, v11.0.0 Sep. 2012.