EUROPEAN COOPERATION
IN THE FIELD OF SCIENTIFIC
AND TECHNICAL RESEARCH

EURO-COST

COST 2100 TD(09) 734
Braunschweig, Germany
2009/Febr/16-18

SOURCE: TSC Signal Theory and Communications Department
Universitat Politècnica de Catalunya
Spain

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Abstract**—3GPP LTE is the evolution of the UMTS which will make possible to deliver next generation high quality multimedia services according to the users' expectations. Since Radio Resource Management (RRM) has been recognized as a key point to successfully accomplish this target, the performance evaluation of a multi-cell resource allocation scheme applied to LTE downlink (DL) is presented in this paper. A semi-distributed and a fully-distributed RRM framework are compared on the basis of the obtained system throughput. Detailed link level simulations have also been carried out to properly back up the system level results.**

I. Introduction

3GPP LTE is the evolution of the UMTS which will make possible to deliver next generation high quality multimedia services according to the users' expectations [1]. OFDM/OFDMA have been selected by 3GPP as the physical layer and multiple access schemes for DL LTE. Because of the high degree of flexibility in the allocation of radio resources to UEs, the optimization of resource allocation can become very complex. In order to achieve a high frequency reuse, the problem of RRM must be addressed jointly with the inter-cell interference management and from a multi-cell perspective. The key RRM function is the scheduling of DL transmissions to the different users performed at the Base Station (eNB) at both Time Domain (TD-PS) and Frequency Domain (FD-PS) [2], where time is divided into 1 ms Transmission Time Intervals (TTI) and frequency into 180 kHz Physical Resource Blocks (PRB). The RRM framework is essentially decentralized, but in the literature two different approximations have been considered: those assuming some type of fixed reuse pattern depending on the UE path loss (or other measured or estimated parameter) [3], or those without prefixed partitions but still using some sort of centralized RRM entity co-located at one of the eNBs [4]. The role of this centralized entity is to gather measurements from several neighbouring eNBs in order to coordinate their scheduling processes on a coarse time scale. In addition to inter-cell interference mitigation several other aspects, like keeping the users' QoS guarantees, signalling overhead minimisation, fairness among users, adaptation to traffic patterns and implementation issues, need to be addressed in the RRM design at eNB level. The resulting problem is very complex and it is often intractable in an analytic way. So finally simulations must be performed, under as realistic as possible scenarios, in order to obtain results which allow us to better trade-off among those factors.

The aim of this paper is to evaluate the performance of a multi-cell radio resource allocation methodology under the LTE framework, considering both a semi-distributed and a fully-distributed algorithm. The system level simulator is supported by a detailed E-UTRA link level simulator to perform Link Adaptation (LA) through Adaptive Modulation and Coding (AMC) including Hybrid ARQ (HARQ) and a Multipath Fading Channel.

The paper is organized as follows: in section II the multicell scheduling framework is described. In section III the system model and problem formulation for the scheduling algorithms are given. Section IV mentions E-UTRA DL link level simulator, section V discusses the simulation results and finally section VI addresses future work and conclusions.

II. Description of the multi-cell RRM framework

In this section we describe the multi-cell scheduling framework and the assumptions that have been made. The proposed semi-distributed scheme controls inter-cell interference with a coarse time resolution (a super-frame (SF)), while fairness and further throughput maximization are controlled within a smaller time scale by the eNB decentralized scheduling algorithm (TTI RRM), see Fig. 1.

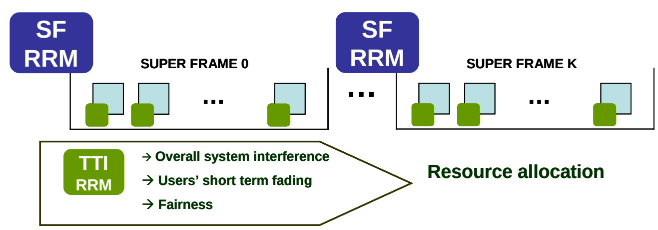

Fig. 1 Temporal structure of the RRM scheme

A PRB can only be assigned to one UE within a cell, but neighbouring cells may reuse the same PRB depending on the UE interference level.

A. SF RRM

Super-Frame RRM is oriented to coordinate a set of neighbouring eNBs in order to reduce and bound the inter-cell interference between cells. The eNB performing the SF RRM has available, at the beginning of each super-frame, the signal to interference plus noise ratio (SINR) of all the UEs served by the set of coordinated eNBs as well as the identifier of the DL dominant interferer for each UE.

SF RRM algorithm decides the set of PRBs assigned to each eNB for the next super-frame and recommends the number of PRB to be assigned to the specific UEs by estimating and bounding the inter-cell interference through the Throughput Marginal Utility (TMU) of the users, [4].

B. TTI RRM

Final resource allocation is done at each eNB, which based on recommendations given by SF RRM, decides the pairing between PRBs and UEs trying to locally optimize the throughput by considering the instantaneous UE's fading. Fairness among users is also considered by applying a Proportional Fair (PF) scheduling algorithm, using as metrics the throughput foreseen for the next TTI normalized by the average accumulated throughput for that UE. Alternatively, a Maximum Throughput (MT) scheduling (similar to the one used in HSPA) has been tested. MT scheduling is oriented to serve first UEs with higher SINR, being the metrics in this case the next TTI foreseen throughput [4].

The algorithm allows classifying the UEs in different classes based on their reported SINR, see [5]. Scheduling is applied independently for the different classes in a Round Robin scheme. High SINR users of different cells, because of the low interference level, are allowed to simultaneously use all the PRBs (reuse 1). Medium or low SINR users of different cells cannot use the same PRB simultaneously.

Finally, the fully-distributed scheduling scheme entirely disables SF RRM, maintaining only the TTI RRM algorithm, because the mapping between the PRBs used by the different cells has been already fixed in terms of a reuse 1 or 3 depending on fixed SINR thresholds.

III. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a regular cell deployment with B eNBs. Each eNB has available a total of N PRBs. There are a total of M users in the system distributed along the B eNBs, so that $M=\sum M_b$ (where M_b is the number of users served by eNB b). We define the following notation according to Table I.

TABLE I
NOTATION DEFINITION

Meaning	Notation	Definition
UE PRB allocation.	$\mathbf{Y}\in\Re^{MxN}$ $y_{mn}\in\{1,0\}$	y_{mn}=1 when PRB n is assigned to user m and 0 otherwise.
Power allocation to PRB	$\mathbf{P}\in\Re^{BxN}$ $\mathbf{0}\le P_{bn}\le P_{max}$	P_{bn} is the power transmitted by eNB b in PRB n. $P_{\max}$ is the maximum transmission power per PRB available at the eNB
Path loss	$\mathbf{L}\in\Re^{MxB}$	L_{ib} is the path loss (including shadowing fading) between base b and user i

The SINR measured by user i on PRB n is calculated as:

$$SINR_{in} = \frac{P_{\hat{i}n} / L_{i\hat{i}}}{\sigma^2 + \sum_{\substack{b=1 \\ b\neq\hat{i}}}^{B} \left(\sum_{m=1}^{M_b} y_{mn} \cdot P_{bn} / L_{ib} \right)} \quad (1)$$

where σ^2 is the UE received thermal noise at PRB n and $\hat{i}$ is the serving eNB for user i.

The number of bits that the serving eNB can transmit on PRB n to user i is T_{in}, which depends on the link level throughput achievable by the selected AMC format combination. We assume that the serving eNB always selects the AMC format that maximizes the link throughput for the current SINR, so that we have $T_{in} = f(SINR_{in})$ where $f()$ is the mapping function between the AMC format and PRB capacity. This mapping function has been obtained from link level simulations following the actual settings given in LTE specs. The H-ARQ mechanism and fast fading channel are included in link level simulations. Finally, the system throughput associated to PRB n is given by:

$$T_n = \sum_{i=1}^{M} T_{in} \quad (2)$$

Having defined the previous notation, the problems for both the SF and TTI RRM are formulated as follows:

A. SF problem formulation and algorithm description

The SF RRM problem consists in assigning a number of PRBs (and the transmitted power on that PRB) to eNBs so that the global system throughput is maximized.

$$\underset{Y,P}{\text{Max}} \left(\sum_{n=1}^{N} T_n(Y,P) \right) \quad (3)$$

After obtaining the SINR per UE and the corresponding PRB payload capacity, for each eNB the algorithm sets an upper bound on the number of PRBs that the served UEs can receive. Let's define Q_i as the achievable payload per PRB of UE i. For a generic eNB b, the maximum number of PRBs that UE i can receive (N_i) is obtained by setting:

$$N_1 Q_1 = N_2 Q_2 = ... = N_{M_b} Q_{M_b} \quad (4)$$

where $\sum_{i=1}^{M_b} N_i = N$.

Next step is the Heuristic PRB allocation, in which the algorithm actually deals with the inter-cell interference. Implementation details can be found in [4]. Basically, the algorithm assigns PRBs one by one to the different eNBs considering the degradation on the other eNBs to which that PRB has been already assigned. The order in which the eNBs are checked affects the final results, so after each iteration, the eNBs are sorted in order inversely proportional to the number of PRBs already assigned to them.

B. TTI assignment

Taking as input the set of PRBs assigned to an eNB by the SF RRM and for each served UE, the eNB assigns a specific PRB to the UE with higher TMU for that particular PRB. Also constrains from the SF RRM algorithm on the maximum number of PRBs to be granted for each specific UE are taken into account. If the PF scheduling scheme is applied, with periodicity equal to one TTI a generic eNB *b* assigns a specific PRB *n* to the served UE *m* using:

$$m = \arg\max_{m\in\{1,\dots,M_b\}} \frac{T_{mn}(t)}{\sum_{i=0}^{t-1} T_{mn}(i)} \quad (5)$$

The expression for the MT scheduling scheme is obtained by removing the denominator in (5).

Finally, a simple power control (PC) scheme is implemented just to test if it provides a significant or marginal improvement in the system throughput. Once the SF and TTI RRM algorithms have finished, the PC algorithm is executed: for each PRB and for each UE using simultaneously this PRB, the power of the dominant interferer is reduced in 3 dB, accepting this change only if there is an improvement in system throughput.

IV. DESCRIPTION OF THE E-UTRA DL LINK LEVEL SIMULATOR

In order to feed the system level simulator with the link level performances, a new ad-hoc link level simulator has been programmed in C++ language. The E-UTRA DL link level simulator features an OFDM physical layer in accordance with [9], and has been completely described in [10].

V. SIMULATION RESULTS AND DISCUSSION

Table II lists the parameters used for the simulations. In order to achieve a high time resolution, the simulation uses the maximum bandwidth, but only one PRB is demodulated by the UE. The simulated code block sizes are the smaller ones specified for E-UTRA DL. The obtained link level throughput can thus be considered the E-UTRA DL baseline performance, since higher code block sizes will provide higher throughput figures.

The considered channel model is Extended Pedestrian A (EPA), as specified in [8], with a 3km/h pedestrian speed.

TABLE II
LINK AND SYSTEM LEVEL SIMULATOR PARAMETERS

Parameter	Value
Carrier frequency	2 GHz
Transmission Bandwidth	20 MHz
Sub-carrier spacing	15 kHz
OFDM PHY parameters	CP of 4.69 µs 7 modulation symbols/sub-frame (2 for control)
FFT size	2048
Number of useful sub-carriers	1200
OFDM symbol duration	71.43 µs
Number of sub-carriers per PRB	12
Number of PRBs	100
Sub-frame duration	0.5 ms
TTI length	1 ms
Number of OFDM symbols per TTI	14 (4 for control)
Frame duration	10 ms
Superframe duration	600 ms
Transmission mode	Localized
Power Delay Profile	EPA channel model Pedestrian speed 3 km/h
Channel Coding	Turbo code basic rate 1/3
Code block sizes	40-120 bits
Rate Matching and H-ARQ	According to [9] (release 8). Max 4 IR transmissions.
AMC formats	QPSK: 1/3, 1/2, 2/3, 4/5 16QAM: 1/2 , 2/3, 4/5 64QAM: 2/3, 4/5
Channel estimation	Ideal
Antenna scheme	SISO/MIMO
Cell radius	500 m
Path loss expression	31.5+35log(d[m]) [dB]
Shadowing fading standard deviation	7 dB
Number of active UEs per cell (infinite buffer per user)	15
Number of cells	19 ommnidirectional or 57 sectorial

The antenna gain for the sectorial deployment is given by

$$G_{ant}(\theta) = -min\left[12\left(\frac{\theta}{\theta_{3dB}}\right), G_{max}\right] dB \quad (6)$$
$$\theta_{3dB} = 70º, G_{max} = 20$$

And it's included as an additional term in the propagation losses that already account for path loss, lognormal shadowing and building penetration losses (if indoor users are considered)

Fig. 2 shows the E-UTRA DL throughput for the different AMC formats and H-ARQ in EPA multipath channel at a pedestrian speed of 3km/h.

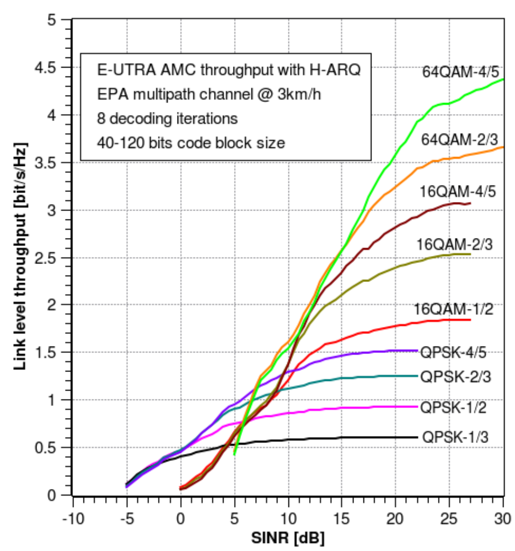

Fig. 2 E-UTRA DL AMC link level throughput with H-ARQ in multipath EPA channel 3km/h

Other figures similar to Fig. 2 and used in this paper are given and explained in detail in [10].

First results of the system level simulator have been performed over 19 omnidirectional cells, collecting statistics only from the central 7 cells in order to avoid border effect. 50 independent simulations have been done to obtain first results (averaging over 350 cells), but more snapshots will be done when all the scheduling algorithms we are interested in, have been programmed. We assume that the users have always data to transmit (infinite buffer traffic model).

Fig. 3 is a histogram of the SINR distribution perceived by the UEs in the central cells of the scenario. The thresholds that have been set up in order to classify the UEs in three different classes for scheduling purposes are:

External UEs: SINR ≤ 3 dB
Intermediate UEs: 3dB < SINR ≤ 12dB
Internal UEs: 12dB < SINR

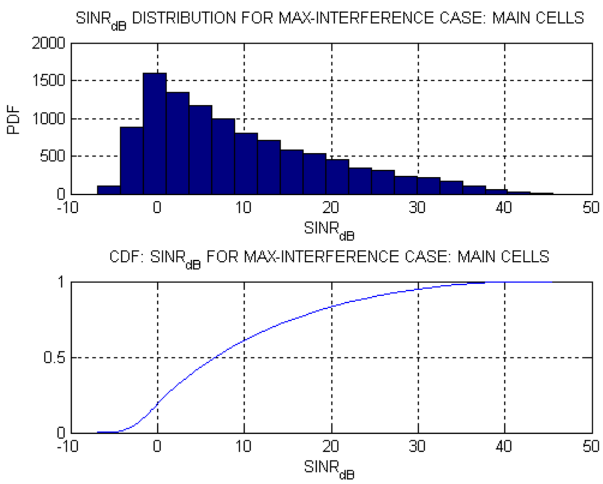

Fig. 3. Histogram and CDF of the SINR perceived by the UEs in the central cells of the scenario.

As uniform users distribution is considered it can be observed that approximately 33% of users have a SINR lower than 3 dB (external users), 33% experience a SINR between 3 and 12 dB (intermediate users), having the rest a SINR higher than 12 dB (internal users) but in this case showing a great dispersion in the SINR value that is expected to become a higher difference in accepted throughput values for this kind of users when compared with the rest.

In Fig. 4 the histogram of the average cell throughput and the corresponding cdf is given for a SISO system. The three type of users can be clearly distinguished: those with low SINR (cell-edge users) will transmit using a low order modulation (QPSK) and coding rate, while users with high SINR (close to the base station) will be allowed to use 64QAM and coding rates close to one. This is clearly distinguished because in one TTI the cells will attend simultaneously only one user's category: internal, intermediate or external. So the categories will be served in a Round Robin (RR) temporal scheduling, which simplifies considerably the algorithm implementation. Another aspect that can be clearly appreciated is that there is a higher dispersion in the throughput associated to high SINR users. CDF function shows the typical three steps performance with jumps around 33%, 66% and 99% (corresponding to the RR time scheduling), as the dispersion increases when SINR is higher, the slope of the step is progressively reduced.

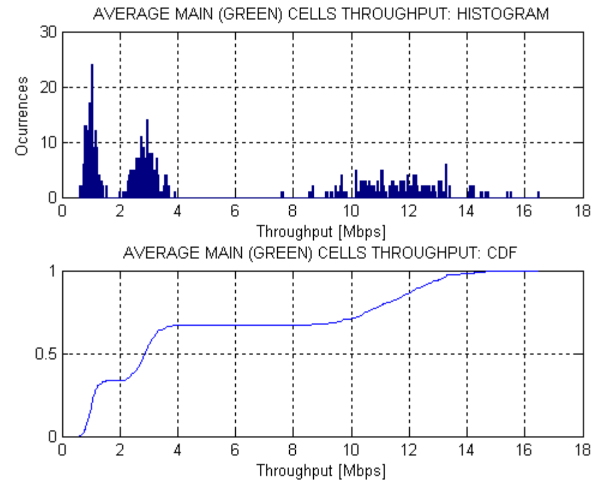

Fig. 4. Histogram and CDF of the DL average cell throughput (SISO)

In Fig. 5 the same analysis is given, but now for the scenario that includes a MIMO (2x2 with spatial multiplexing) antenna system. It can be appreciated that the shape of both the histograms and the cdf is similar than in the previous figure, but the throughput has clearly increased. Without MIMO the maximum average cell throughput was around 14 Mbps, while with MIMO its is around 30 Mbps.

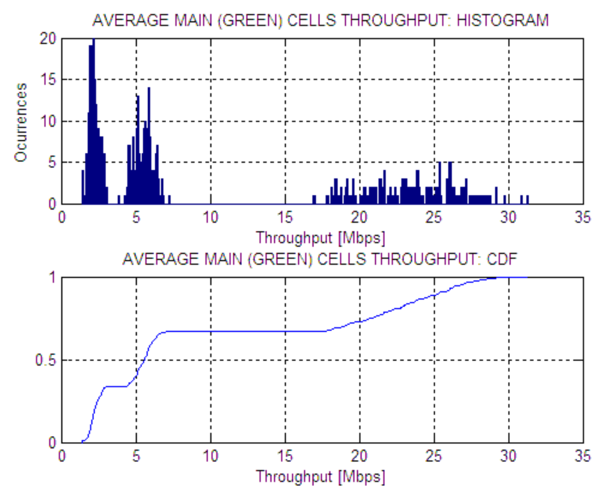

Fig. 5. Histogram and CDF of the DL average cell throughput (MIMO 2x2 with spatial multiplexing)

VI. LIMITATIONS, FUTURE WORK AND CONCLUSIONS

3GPP specifications do not include scheduling schemes, giving the vendors and operators the opportunity to define their own proposals. So it is a field where intensive research activity has been done in last year's. The scheme proposed and analyzed here is the first approximation to both time and frequency scheduling in 3G-LTE networks done by the research team. It is not the best option, and has several drawbacks and serious limitations that will be described here, while defining also other schemes that will be tested in future research work.

One of the main drawbacks is that it has a rigid temporal scheduling. Even in the case of having no internal users, during one third of the time, the cell could not attend other users. This lack of flexibility is comparable to the case of using a fixed reuse scheme K=3, assigning a cell 1/3 of the PRB. Even in the case of low traffic in this cell, their resources could not be used by the surrounding cells. For this reason the average cell throughput is around 1/3 of the throughput presented by other authors in theoretical optimal scheduling (if the total 20 MHz bandwidth, this is the 1200 subcarriers, is given to a single user transmitting the best option, 64 QAM and with no codes, we will have 6 bits x 1200 subcarriers/OFDM symbol x 10 OFDM symbols/TTI = 72 Mbps; considering the transmission only in one third of the time 24 Mbps will be obtained) instead of the around 14 Mbps that we have. But there are other limitations that made this scheme non practical, it assumes that there is some coordination between cells when deciding the frequency scheduling, so that at super-frame level, there is a eNodeB acting as “Radio Network Controlling” and deciding which set of PRBs will be assigned to the different cells. There is an intrinsic advantage in not having fixed/pre-assigned PRBs to cells, but this increases the signaling, the special eNodeB should know all the quality parameters of the users and the cells under its control, to be able to take the appropriate decisions. There are more simple but not so flexible algorithms based in fixed frequency reuse, frequency partitioning, global reuse changing transmitted powers, etc. that seem more simple in their definition, offering also good performance. These are the algorithms we are interested in for the next months.

Another limitation, not intrinsic to the algorithm, is that we have done all the simulations without considering the effect of multipath fading over SINR, that is, using wideband average values. In a more realistic assumption Exponential Effective SINR (EESINR) has to be used to obtain the Channel Quality Indicators (CQIs) for the different RBGs.

In each TTI, for each UE and for all the RGBs the EESINR must be computed. To do so, in the case of 20 MHz bandwidth it is necessary to obtain, ideally for each sub-carrier (k), the instantaneous signal to noise ratio at the system level simulator. This is given by:

$$\gamma_k = P(k) \times \overline{SINR} \times \left(\frac{N}{N + N_p} \right) \times \frac{R_D}{N_{SD} / N_{ST}} \qquad (7)$$

Being N and N_p the FFT size and the cyclic prefix length, N_{SD} and N_{ST} the number of data and useful subcarriers per TTI respectively and R_D the % of maximum total available power allocated to the data subcarriers [10]. P(k) represents the frequency selective fading power profile value for the k^{th} subcarrier, calculated as:

$$P(k) = \left| \sum_{p=1}^{\text{paths}} M_p A_p e^{j[\theta_p - 2\pi f_k T_p]} \right|^2 = \left| \sum_{p=1}^{\text{paths}} M_p A_p e^{j\theta_p} e^{-j2\pi f_k T_p} \right|^2 \qquad (8)$$

Being M_p and θ_p and T_p the amplitude, phase and relative delay of the p^{th} multipath path component (assumed constant during a TTI observation period), f_k the relative frequency offset of the k^{th} subcarrier within the spectrum, and A_p is the amplitude value corresponding to the long-term average power for the p^{th} path (assuming that the sum of the long-term path powers in the channel model has been normalized),

The EESIR is obtained from the γ_k by:

$$EESIR = -\beta \ln\left(\frac{1}{N_u} \sum_{k=1}^{N_u} e^{-\frac{\gamma_k}{\beta}} \right) \qquad (9)$$

being N_u the number of useful subcarriers in a RGB (for 20 MHz bandwidth a RGB is composed of 4 PRBs and each PRB has 12 subcarriers, so N_u is equal to 48 subcarriers). Since there are 15 different values of β, each one corresponding to a different combination of modulation and coding (look up tables from the link layer simulator), there will be 15 different values of EESSIR. There is also a mapping between EESIR and BLER. The UE should start calculating the EESSIR for the combination of maximum throughput (maximum modulation order and higher coding rate). If for this combination the BLER is lower than 0.1 it is not necessary to obtain the values for the other fourteen. If the BLER is higher than 0.1 the procedure is repeated with the next modulation and code combination, and so on. With this procedure what is finally obtained is that, for each RGB, the UE reports to the eNodeB a CQI which is an index between 0 and 15 (0 means out of range) that gives the information about the higher modulation and coding scheme that can be used in each RGB.

Another limitation of the results presented so far is that the minimum number of resources assigned to a user is a PRB instead of a RBG. In this case is very easy to change the parameters to account for this more realistic assumption.

Finally it seems interesting to compare the performance with those obtained using a completely distributed system, where each cell has to choose the best RBGs and power level to be assigned to each user, based only on the CQIs coming from the UE. Some of the typical frequency scheduling algorithms are: frequency reuse with different patterns and frequency partitioning [12].

As this algorithms combine frecuency with power scheduling, it is convinient to define an utility factor that combines both parameters.

$$Utility = \frac{1}{NRBGs \cdot P_{T,max}} \cdot \sum_{i=1}^{NRBGs} P_{t,i} = \frac{P_{T,tot}}{NRBGs \cdot P_{T,max}} = \frac{P_{T,tot}}{P_{T,tot\,,max}} \qquad (10)$$

being $P_{T,tot}$ the total power transmitted for the global bandwidth, and $P_{T,max}$ the maximum transmitted power per RGB. $P_{T,tot,max}$=NRBGs·$P_{T,max}$ (46 dBm is considered as the maximum total transmitted power for a 20 MHz bandwidth).

Soft Frequency reuse schemes: each cell can independently adapt to different frequency reuse strategies (FR-Modei) depending on the cell load and on the measured interference levels. FR-Mode1 will be a simple total reuse (the cell uses all the RBGs with the same transmitted power) specially adapted for low cell load (therefore low interferences), while FR-Mode3 is a fixed reuse 3 partition (each cell uses 1/3 of the RBGs) that should be used for high cell load (high interference level). An intermediate mode, FR-Mode2, with soft frequency reuse is also considered (each cell uses 1/3 of the RBGs transmitting maximum power and the others 2/3 with a reduced power level).

In the simulator only one model, named Soft Frequency Reuse is programmed considering that $P_{T,max}$ is the maximum transmitted power associated to the prioritized RBGs, and that $\varepsilon \cdot P_{T,max}$ is the transmitted power associated to the non-prioritized RBGs. If ε=1 all the RBGs have the same transmitted power (Model 1 with reuse 1), while if ε=0 only 1/ of the RBGs can be used (Model 3 with reuse 3). The utility function can be expressed as:

$$Utility = \frac{1}{NRBGs \cdot P_{T,max}} \cdot \left[\frac{NRBGs}{3} \cdot P_{T,max} + \frac{2 \cdot NRBGs}{3} \cdot \varepsilon \cdot P_{T,max}\right] = \frac{1+2\varepsilon}{3} \quad (11)$$

being the NRBGs the number of RBGs in the system (25 for 20 MHz).

Changing the low transmitted power level (changing ε), the system could adapt to different intermediate loads while controlling the interferences. In FR-Mode2 the cell has to try to reserve the high power subband to the cell-edge users, more affected by interferences, so the quality of these users can be maintained. The way to classify users in cell-edge (outer region) or not (inner region) is the same as described previously according to their SINR, EESIR, CQI parameters.

Models 2 and 3 require the introduction of some initial coordination or the stablishment of some priorities, to decide that, for example, cell A has the first third of the RBGs as her prioritary assignment, while cells B and C the second and third respectively. If this priorities are initially fixed by the designer, even in Mode 1 (low traffic conditions) a cell will use only one third of the bandwidth causing no interferences over the others. Furthermore, the threshold traffic or load levels, when the system has to change the mode, have to be obtained by simulation.

This is a simple scheme to be tested, being probably one of its drawbacks the fact it is more oriented to reduce the interference level instead of maximizing the overall cell throughput. The algorithm assigns the low transmitted power level RBGs (then reducing the potential SINR) to the users close to the base station that could have the maximum throughput.

Frequency Reuse Partitioning: the main difference is that the sub-band transmitting $\varepsilon \cdot P_{T,max}$ will be the same in the 3 cells (reuse 1), while the sub-band transmitting $P_{T,max}$ is divided between the cells so each cell gets one third (reuse 3). So there is an additional parameter to be defined, β, that is the partition of the two bands with different reuse.

$$Utility = \frac{1}{NRBGs \cdot P_{T,max}} \cdot \left[\beta \cdot NRBGs \cdot \varepsilon \cdot P_{T,max} + \frac{(1-\beta) \cdot NRBGs}{3} \cdot P_{T,max}\right] = \frac{\beta \cdot (3\varepsilon - 1)}{3} \quad (12)$$

The parameters that should be analyzed and compared with previous algorithm are the SINR histograms, the cdf of the average cell throughput, for the different scheduling models, and changing the power levels and band partition, through a variation of ε and β.

With this, a complete set of different scheduling strategies commonly referenced in the literature, will be analyzed and compared in detail. The next step will be to implement a dynamic simulator to be able to test the influence of time variations, finite buffers, traffic models and multipath variation.

ACKNOWLEDGMENT

This work is supported by Spanish National Science Council under grant TEC2008-06817-C02-02.

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