Novel eICIC Scheme for HetNets Exploiting Jointly the Frequency, Power and Time Dimensions

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***Abstract*— User demand for capacity and high data rate applications imposes the need for new technologies able to cope with these challenges. Fourth Generation cellular networks have set the initiative for a technology evolution that will surpass the constraints and provide better quality of service and improved performance. In this context, Heterogeneous Networks (HetNets) deployments, combining a variety of different cell sizes, are considered in the literature in order to enhance the coverage and capacity of cellular systems. However, they require enhanced techniques especially for the user-to-cell association, resource allocation and interference management processes. On that respect, in this work we present a novel scheme that exploits jointly the frequency, power and time dimensions for interference mitigation in order to balance the trade-off between interference reduction to small cell users and throughput degradation for macrocell users. Simulation results have shown that the proposed solution utilizes more efficiently the available resources compared to a conventional scheme and boosts the capacity up to 45%.**

***Index Terms*— Heterogeneous Networks, Cell Range Expansion, Almost Blank Subframes, enhanced Inter-cell Interference Coordination.**

I. Introduction

Mobile technology evolution is driven by the user demand in terms of capacity and high data rate applications. On that respect, the deployment of evolved radio technologies, like Long Term Evolution (LTE) and LTE-A (Advanced), aims to fulfill the exponentially growing service requirements. Initially, cellular systems were based on homogeneous deployments of macrocells, with some micro/pico cells deployed under special situations (e.g., traffic hotspots). These conventional networks however, have been proved inadequate to cope with the uneven nature of the user distribution and the data traffic [1].

An attractive solution to the above mentioned problem is the addition in the current deployments of small cells such as pico and/or femto cells. Networks consisting of these elements are known as *Heterogeneous Networks (HetNets)* and are gaining the interest of the researchers and Standardization Bodies [2] as they enhance the coverage in hotspot areas, accommodate high data rate transmissions and improve the network performance [1]-[3]. Nevertheless, HetNets also introduce a number of challenges such as the optimization of user-to-cell association, resource allocation and interference management.

Conventional user-to-cell association methods based on measured received signal strength (RSS) or Signal to Noise and Interference (SINR) ratio (i.e. the UE connects to the cell with the highest RSS or SINR) [4] may be suboptimal in the case of HetNet deployments because of the lower transmit power of small cells, which reduces the number of users that can be connected to them and thus the traffic that is offloaded from the macrocells. To overcome this issue, a technique known as Cell Range Expansion (CRE) is introduced [5][6]. It consists in extending the small cells coverage footprint by adding a cell bias in the measured RSS or SINR. This comes at the cost of a major interference from the other cells particularly for those users in the expanded region that are connected to the small cell but receive higher power from the macrocell.

Therefore, in LTE-A, enhanced Inter-Cell Interference Coordination (eICIC) techniques [7] have been proposed to comply with the new requirements of the HetNets including CRE. Subframe alignment [8] is a Time-Domain eICIC scheme that divides the subframes in two types, Normal and Almost Blank Subframes (ABS). The purpose is that the cell that generates interference is not allowed to transmit user data during an ABS subframe giving the opportunity to the victim cell to transmit under reduced interference. In this way, by avoiding data transmission during ABS subframes in the macrocell, these subframes can be used by the small cell users in the expanded region, so that they will suffer from less interference. An ABS duty cycle calculation method is proposed in [9], where the authors also include a load balancing algorithm. The combination of the two schemes results in better use of resources and user throughputs. In [10], a distributed approach for synchronous ABS is presented where the authors exploit dynamic programming to determine the victim users and the optimal number of ABS.

In this way, CRE and the eICIC concepts have been proved to get significant improvements. However, the available resources are underutilized since the macro cell is not allowed to transmit data during the ABS subframes, which may lead to degradations in the achieved throughput. Therefore, strategies making use of ABS and CRE concepts need to be carefully devised according to the trade-off between interference reduction in the small cells and throughput degradation in the macro cells. Under this framework, in this paper we propose a novel approach that allows a better exploitation of the system resources according to the specific small cell deployment and the current traffic load by jointly exploiting the frequency, power and time dimensions, which are usually addressed separately.

The rest of the paper is organized as follows. In Section II, the system model is described. Section III gives the details of the proposed solution. The simulation results are presented in Section IV and finally, Section V includes the most important conclusions and the future work.

II. SYSTEM MODEL

The system used in this work is comprised by a set of $i = 1, \ldots, M$ macrocells, and a set of $k = 1, \ldots, S$ small cells. A set of users U are non-homogeneously distributed in the scenario, forming some hot spot areas with higher user density than other parts. The user-to-cell association is carried out according to the measured RSS with CRE being applied and with the cell bias denoted as $\Delta\ (dB)$. As a result, the set of users connected to the i^{th} macrocell is denoted as $U_{M,i}$ and the set of users connected to the k^{th} small cell is denoted as $U_{S,k}$. The users in the k^{th} small cell are further classified as the subset of CRE users ($U_{CRE,k}$), which are the users that belong to the extended region of the k^{th} small cell (i.e. users that are connected to the small cell but they receive a higher RSS from the macrocell) and the subset of normal users ($U_{N,k}$), which are the users connected to the k^{th} small cell and receive the higher RSS from the small cell. Note that $U_{CRE,k} \cup U_{N,k} = U_{S,k}$.

Communication in the downlink direction is assumed. The resource allocation follows the LTE specifications, where the frequency dimension is organized in a total of *numRB* Resource Blocks (RBs) of bandwidth B_{RB}=180 kHz and the time dimension in subframes of 1 ms organized in frames of 10ms. As such, the available RBs in a frame are numbered as *RB(f,t)* where *f*=1,...,*numRB*, and *t*=1,...,10. It is assumed that each cell carries out the scheduling in each frame to decide the allocation of the RBs to the users. The smallest allocation unit to a user is one RB in one subframe. ABS technique is applied with μ denoting the number of the ABS subframes per frame. Non-ABS subframes are denoted as Normal subframes.

The total propagation losses in the *RB(f,t)* for a user $u \in U$ with respect to the i^{th} macro and the k^{th} small cell are denoted as $L_{M,u,i,RB(f,t)}$ and $L_{S,u,k,RB(f,t)}$, respectively. They include the shadowing and the fast fading due to multipath.

III. PROPOSED SOLUTION

The key idea of the proposed solution is to improve the current trade-off between interference reduction in the small cells and throughput degradation in the macrocell due to the silent periods during ABS frames, based on jointly considering the frequency, power and time dimensions when deciding the allocation of users to RBs. In particular, the proposed approach assumes that a more efficient use of the resources can be achieved to increase the macrocell throughput if, instead of totally avoiding data transmission during the ABS subframes, smart mechanisms are applied that allow transmission in these subframes under special constraints to avoid generating an excess of interference to the small cells. Such conditions are expressed in terms of the allowed RBs in the frequency domain or the maximum allowed transmit power. In particular, considering the i^{th} macrocell and the small cells falling in the coverage area of this macrocell, the strategy makes the following distinction, as shown in Fig. 1.

Case 1: Whenever the small cells are located at a high distance from the macrocell (i.e. the distance d_s between the macrocell site and the closest small cell site is above a certain threshold *Ths*), we take advantage of the fact that the small cell users suffer inherently less interference from the macro cell. As such, transmissions of the macrocell users on the ABS subframes could be allowed with the restriction of a lower transmit power. In order to do so, the macro cell is split in two parts, the outer and the inner. This is done by classifying as outer users the macrocell users with an average propagation loss (i.e. without including fast fading) to the macrocell above a certain threshold (L_{th}) and as inner users the macrocell users with average propagation loss below the threshold. The subset of outer users of the i^{th} macrocell is $U_{O,i}$, and the subset of inner users is $U_{I,i}$. The value of the L_{th} is set such that, according to the propagation model, the distance associated to L_{th} is lower than the distance d_s to the closest small cell.

In this way, the inner users are allowed to be allocated in the RBs of the μ ABS subframes with reduced power level, while outer users can only be allocated in the RBs of Normal subframes. Then, the transmit power per RB for the i^{th} macrocell will be $P_{TM,i,low}$ for the ABS subframes allocated to inner users and $P_{TM,i,high}$ for the Normal subframes allocated to either outer or inner users.

As for the resource allocation in the small cell, the CRE users are allocated only in ABS subframes and the normal users are allocated preferably in ABS subframes but they can also use normal subframes when there are not sufficient RBs in the ABS subframes. The transmit power per RB of the k^{th} small cell will be $P_{TS,k}$ in all the subframes allocated to small cell users. The abovementioned allocation criteria for both macro and small cell users in Case 1 are graphically summarized in Fig. 1 (a).

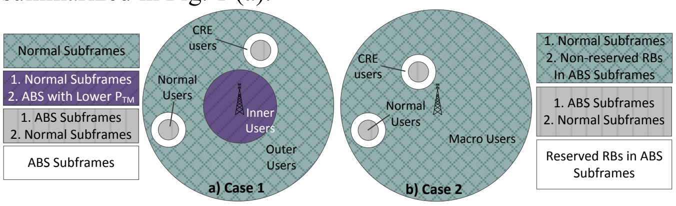

Fig. 1: Allocation criteria for Case 1 (a), and Case 2 (b)

Case 2: If any of the small cells is located close to the macro cell, (i.e. the distance d_s between the macrocell and the closest small cell is below threshold *Ths*) the small cell users are more susceptible to the interference from the macro; therefore a simultaneous use of the ABS subframes is not possible even if the macrocell would transmit with lower power in these subframes. As such, an alternative strategy is applied where the splitting takes place in the frequency domain. We define a number of RBs $\varepsilon \leq numRB$ as especially reserved RBs in each ABS subframe. These reserved RBs will not be used by the macrocell for data transmission. Instead, they will be mainly devoted for the CRE small cell users since they are those that are more sensitive to the macrocell interference. Then, the macrocell users will be allocated to either normal subframes or to the $(numRB - \varepsilon)$ non-reserved RBs in the ABS subframes. As such, we avoid having the macrocell completely silenced during an ABS subframe, increasing in this way the macro capacity. The key factor here is that the number ε of reserved RBs may be reconfigured depending on the amount of the CRE users. In particular, in this work we assume the following:

$$\varepsilon = \min([\alpha \cdot numCRE], numRB) \quad (1)$$

where α is a parameter of the algorithm, *numCRE* is the total number of CRE users in the small cells within the coverage area of the i^{th} macrocell and [·] represents the rounding operation to the nearest integer value.

In this way, if there are few CRE users, we reduce the value of ε, while as the number of CRE users increases we approach the conventional ABS scenario where the macrocell cannot transmit in any of the RBs (i.e. $\varepsilon = numRB$). The CRE users of the small cells will be allocated only in the reserved RBs of the ABS subframes, while the normal users will be allocated preferably in the ABS subframes (both reserved and non-reserved), but they are allowed to utilize the Normal subframes if there are not sufficient RBs in the ABS subframes. The transmit power per RB of the i^{th} macrocell in this case will be $P_{TM,i,high}$ for all the subframes. In turn, the transmit power per RB of the k^{th} small cell will be $P_{TS,k}$. The abovementioned allocation criteria for both macro and small cell users in Case 2 are graphically summarized in Fig. 1 (b).

The pseudo-code of the scheduling algorithms for allocating the different RBs to the users according to the abovementioned proposed strategy are presented in Fig. 2 and Fig. 3 for the macrocells and the small cells, respectively.

Scheduling Algorithm in the i-th macrocell for a frame

```
compute m_{u,RB}(f,t) for each user u∈U_{M,i} ,for all RBs
initialize Σ_u=0 for each user u∈U_{M,i}
for each normal subframe t              //Normal subframes
  for (f=1;f<=numRB)
     U_aux=set of users in U_{M,i} with R_{u,RB(f,t)} ≥ R_{b,min} and Σ_u ≤ R_{b,max}
     u* = arg max_{u∈U_aux} m_{u,RB(f,t)}
     allocate RB(f,t) to user u* with P_{TM,i,High}
     Σ_{u*}= Σ_{u*}+ R_{u*,RB(f,t)}
  end for
end for
for each ABS subframe t                 //ABS subframes
  if (ds<Ths)                           // Case 1
    for (f=1;f<=numRB)
       U_aux=set of users in U_{I,i} with R_{u,RB(f,t)} ≥ R_{b,min} and Σ_u ≤ R_{b,max}
       u* = arg max_{u∈U_aux} m_{u,RB(f,t)}
       allocate RB(f,t) to user u* with P_{TM,i,Low}
       Σ_{u*}= Σ_{u*}+ R_{u*,RB(f,t)}
    end for
  end if
  else if (ds>Ths)                      // Case 2
    for (f=1;f<=numRB- ε)               //only non-reserved RBs
       U_aux=set of users in U_{M,i} with R_{u,RB(f,t)} ≥ R_{b,min} and Σ_u ≤ R_{b,max}
       u* = arg max_{u∈U_aux} m_{u,RB(f,t)}
       allocate RB(f,t) to user u* with P_{TM,i,High}
       Σ_{u*}= Σ_{u*}+ R_{u*,RB(f,t)}
    end for
  end else if
end for
```

Fig. 2: Macrocell Scheduling Algorithm

The scheduling follows the principles of the Proportional Fair (PF) algorithm [11] in order to prioritize the different users. In particular, for each user u (where $u \in U_{M,i}$ when doing the scheduling for the users in the i^{th} macrocell and $u \in U_{S,k}$ for the users in the k^{th} small cell) the following priority metric is defined associated with each $RB(f,t)$:

$$m_{u,RB(f,t)} = \frac{R_{u,RB(f,t)}}{W_u} \tag{2}$$

$R_{u,RB}(f,t)$ is the achievable bit rate by the user in $RB(f,t)$ given by:

$$R_{u,RB(f,t)} = B_{RB} \log_2\left(1 + \left(\frac{S}{N}\right)_{u,RB(f,t)}\right) \tag{3}$$

where $(S/N)_{u,RB(f,t)}$ is the signal to noise and interference seen by the user in $RB(f,t)$. In turn, W_u is the bit rate experienced by the user averaged over a window of the last T_W frames, so it depends on the past allocation of RBs to this user. After each frame, W_u is updated taking into account the actual bit rate achieved by user u in its allocated RBs. In order to avoid allocating an RB with very low bit rate, a user u is only considered as candidate for the assignment of $RB(f,t)$ if $R_{u,RB}(f,t)$ is above a specific threshold $R_{b,min}$. In addition, the maximum number of RBs that can be allocated to a single user u in one frame is limited by the fact that the aggregation of the bit rates $R_{u,RB}(f,t)$ in the RBs allocated to this user should be below a maximum value $R_{b,max}$. This aggregated bit rates for a given user u is denoted as Σ_u in the pseudo-code, and is updated each time that an RB is allocated to this user u.

Scheduling Algorithm in the k-th small cell for a frame

```
compute m_{u,RB}(f,t) for each user u∈U_{S,k} ,for all RBs
initialize Σ_u=0 for each user u∈U_{S,k}
for each ABS subframe t                 // ABS subframes
  if (ds<Ths)                           // Case 1
    for (f=1;f<=numRB)                  //all the RBs
       U_aux=set of users in U_{CRE,k} with R_{u,RB(f,t)} ≥ R_{b,min} and Σ_u ≤ R_{b,max}
       if U_aux = ∅
          U_aux=set of users in U_{N,k} with R_{u,RB(f,t)} ≥ R_{b,min} and Σ_u ≤ R_{b,max}
       end if
       u* = arg max_{u∈U_aux} m_{u,RB(f,t)}
       allocate RB(f,t) to user u* with P_{TS,k}
       Σ_{u*}= Σ_{u*}+ R_{u*,RB(f,t)}
    end for
  else if (ds>Ths)                      // Case 2
    for(f=1;f<= ε)                      //reserved RBs
       U_aux=set of users in U_{CRE,k} with R_{u,RB(f,t)} ≥ R_{b,min} and Σ_u ≤R_{b,max}
       if U_aux = ∅
          U_aux=set of users in U_{N,k} with R_{u,RB(f,t)}>R_{b,min} and Σ_u <R_{b,max}
       end if
          u* = arg max_{u∈U_aux} m_{u,RB(f,t)}
          allocate RB(f,t) to user u* with P_{TS,k}
          Σ_{u*}= Σ_{u*}+ R_{u*,RB(f,t)}
    end for
    for(f=1;f<=numRB- ε)                //non-reserved RBs
          U_aux=set of users in U_{N,k} with R_{u,RB(f,t)}>R_{b,min} and Σ_u <R_{b,max}
          u* = arg max_{u∈U_aux} m_{u,RB(f,t)}
          allocate RB(f,t) to user u* with P_{TS,k}
          Σ_{u*}= Σ_{u*}+ R_{u*,RB(f,t)}
    end for
  end else if
end for
for each normal subframe t              //Normal subframes
  for (f=1;f<=numRB)
     U_aux=set of users in U_{N,k} with R_{u,RB(f,t)}>R_{b,min} and Σ_u <R_{b,max}
     u* = arg max_{u∈U_aux} m_{u,RB(f,t)}
     allocate RB(f,t) to user u* with P_{TS,k}
     Σ_{u*}= Σ_{u*}+ R_{u*,RB(f,t)}
  end for
end for
```

Fig. 3 : Small Cell Scheduling Algorithm

IV. Simulation Results

The evaluation of the performance of the proposed scheme has been carried out through simulations. In this section we describe the scenario used for the evaluation, the simulation parameters and the numerical results.

A. Simulation Scenario

The simulation scenario consists of one macrocell and two small cells. A set of 90 users are homogeneously distributed in the scenario. In addition, a number of users is distributed in form of a hotspot, as seen in Fig. 4, where two different configurations of the positions of the small cells are considered. The number of users in the hotspot is varied in the simulations.

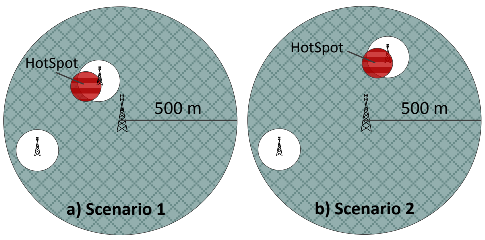

Fig. 4: Simulation Scenarios

The different parameters of the algorithm are shown in Table I. They have been set based on different simulations not shown here for the sake of brevity. Moreover, for case 2 the number of the reserved RBs ε is calculated according to (1) with $\alpha=2/\mu$. This value is obtained considering that each CRE user will require on average 2 RBs to transmit. The general model used for computing the total propagation losses with respect to the macrocells $L_{M,u,i,RB(f,t)}$ and the small cells $L_{S,u,k,RB(f,t)}$ is given by:

$$L(dB) = 128.1 + 37.6 \log d(km) + S - 10 \log F \quad (4)$$

where d is the distance between user u and the cell site, S(dB) is the shadowing modelled as a Gaussian random variable with standard deviation σ = 6 dB, F is the fast fading due to multipath, modelled as an exponential random variable with average 1 assumed independent for each RB and frame.

In case 1 the threshold used for the classification of users into inner and outer is set to L_{th}=101.8 dB. This value corresponds to an inner cell radius of 200m according to the propagation model.

For the evaluation of the system performance we use the average capacity per user. This is computed by averaging over all the simulated frames the capacity C_u that a user u gets in each frame. C_u is computed by aggregating the bit rate in all the RBs allocated to the user u in this frame, that is:

$$C_u = \sum_{RB(f,t) \text{ allocated to user u}} B_{RB} \log_2\left(1+\left(\frac{S}{N}\right)_{u,RB(f,t)}\right) \quad (5)$$

where $(S/N)_{u,RB(f,t)}$ is the signal to noise and interference ratio experienced by user u in the $RB(f,t)$.

B. Numerical Results

The results presented here are the average of 100 experiments, where in each experiment a different random user distribution has been considered. For each experiment a total of 1000 frames are simulated. The proposed strategy is compared against the classical CRE-ABS reference scheme

TABLE I
Simulation Parameters

numRB	Number of RBs	25
μ	Number of ABS subframes	1 to 6
Δ	Cell Bias	3 dB
$P_{TM,i,high}$	Macro Transmit Power (high level)	29 dBm
$P_{TM,i,Low}$	Macro Transmit Power (reduced level)	11 dBm
$P_{TS,k}$	Small cell Transmit Power	6dBm
Ths	Small Cell minimum distance Threshold	250m
T_W	Window size	10 frames
P_N	Noise Power (per RB)	-115.5 dBm
$R_{b,min}$	Minimum bit rate threshold	50 Kbps
$R_{b,max}$	Maximum bit rate threshold	300 Kbps

where the macrocells are not allowed to transmit data in any of the ABS subframes and where the transmit power per RB of the macrocell is constant and equal to $P_{TM,i,high}$. In order to have a fair comparison, the reference scheme also considers the PF prioritization criterion and the $R_{b,min}$, $R_{b,max}$ limitations in the scheduling algorithm as in the proposed approach.

Scenario 1: In this scenario, the two small cells are located at distances 400 and 150 meters from the macrocell site, as seen in Fig. 4 (a). Correspondingly, since *Ths*=250m, the proposed algorithm performs the splitting in the frequency domain following Case 2 as indicated in the Section III. Fig. 5, shows the gain in terms of average user capacity achieved by the proposed scheme with respect to the reference scheme, as a function of the number of users in the hotspot and for different values of the number of ABS subframes μ. As it can be observed, the proposed scheme offers a significant gain that increases with the number of ABS subframes, reaching a value of 45% for μ=6. A key element in achieving this gain is the adjustment of the number of reserved RBs ε according to the number of CRE users in the small cell. In particular, when the number of users in the hotspot (and correspondingly the number of users in the small cells) is small, the algorithm configures the number of reserved RBs ε for transmission in each ABS subframe to be also very small. In contrast, when the number of the small cell users is increased, the algorithm tends to increase the number of reserved RBs ε. In other words, the proposed solution can reconfigure the corresponding resources depending on the traffic load. Note also that in the cases where the number of the ABS subframes is small, for instance 1 or 2, the behavior of the proposed solution resembles that of the reference scheme, since in this case the algorithm leads to ε=*numRB*, meaning that, like in the reference scheme, the macrocell is not allowed to transmit in ABS subframes.

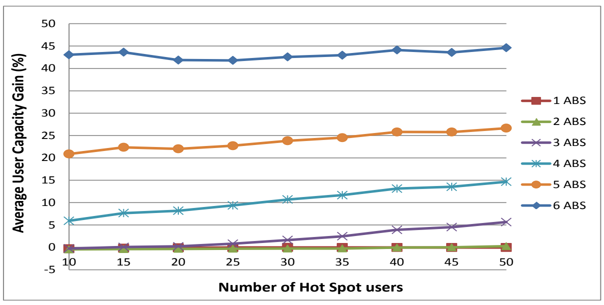

Fig. 5 : Average User Capacity Gain (%)

Fig. 6 and Fig. 7 present separately the capacity gains of the macro and small cell users, respectively. As it can be observed the macrocell users present a very high gain (up to 71%) in their capacity while the small cell users have a small loss (up to 18%), especially when the number of the hotspot users is low. This behavior reflects the good performance of the algorithm, since it is shown that when the load of the macrocell is heavy but the load of the small cells is low, the solution tends to utilize the available resources in such a way that compensates the uneven user distribution. Moreover, as the hotspot users increase, the RBs are configured in a way that still provides some resources to the heavily loaded macro cell, although without generating severe interference to the small cell users. As such, it is shown that the proposed solution can adapt to traffic load changes and balance the capacity among the two types of cells, while keeping the introduced interference to the small cell users in low levels.

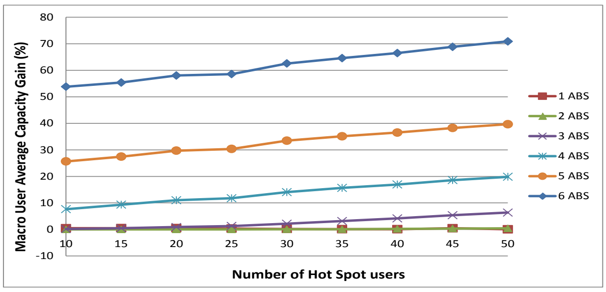

Fig. 6 : Macro Cell User Average Capacity Gain (%)

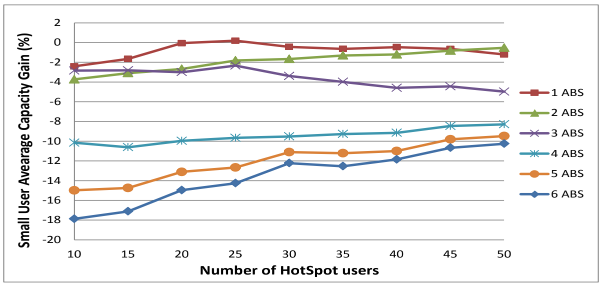

Fig. 7: Small Cell User Average Capacity Gain (%)

Scenario 2: In this scenario, two small cells are located at 400 and 320 m from the macro BS, as seen in Fig. 4 (b). As such, their distance is above the defined threshold *Ths*=250 m and therefore Case 1 is applied, where two levels of transmit power are used for the macrocell. Fig. 8 presents the average user capacity gain compared to the reference scheme in this case. It can be observed that the proposed strategy outperforms the classical approach, and the achieved gain increases with the number of ABS subframes μ, reaching a 16% gain for the case of μ=6. The benefit results from the fact that the proposed solution provides additional resources to the macro users with the corresponding increase of capacity.

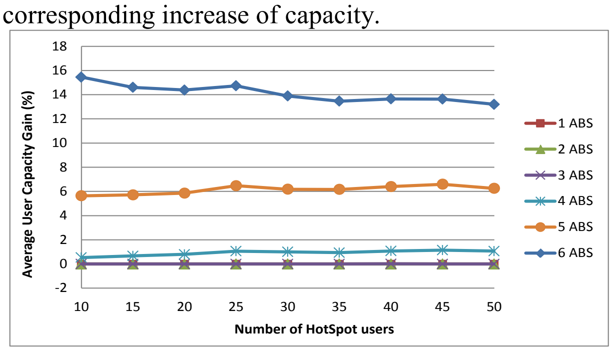

Fig. 8: Average User Capacity Gain (%)

In this scenario the gain achieved by the proposed algorithm is a bit lower than in scenario 1. The reason is that, on the one hand, macrocell inner users are assigned lower transmit power in the ABS subframes while at the same time they receive some interference from the small cell users, so this reduces the gain in the capacity of the macrocell compared to the case 2 applied in the previous scenario. On the other hand, the small cell users experience some capacity reduction; however in this case it is lower than in scenario 1, since the CRE users, instead of being assigned only reserved RBs, are allowed to transmit in all the RBs of the ABS subframes with the cost of some interference that is kept in low levels due to the far distance of the small cells from the macrocell.

V. Conclusions and Future Work

In this work, we have presented a novel solution for interference mitigation in HetNet deployments consisting of macro and small cells. It exploits jointly the frequency, power and time dimensions in order to balance the trade-off between interference reduction to small cell users and throughput degradation for macrocell users. Simulation results have shown that the network resources are utilized in a more efficient way compared to a classical CRE-ABS scheme, leading to average user capacity gains up to 45% depending on the considered scenario. Moreover, the proposed scheme provides a better share of the available capacity among the macro and the small cell users.

Despite the benefits brought of the proposed solution, there is still room for a better exploitation of the resources, as well as for the minimization of the generated interference. As such, as future work our target is to optimize the different parameters involved in the proposed algorithm, such as the transmit power levels, the number of ABS subframes, the number of reserved RBs, the CRE bias, and the threshold to split between inner/outer users.

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