On Enhancing Almost Blank Subframes Management for efficient eICIC in HetNets

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***Abstract*—Heterogeneous Networks (HetNets) have been a crucial point in the evolution of mobile networks that boost the network performance with the addition of small cells. The use of Enhanced ICIC (eICIC) techniques such as Almost Blank Subframes (ABS) has been introduced in HetNets to protect the small cells from high interferences. However this is done at the expense of lower macrocell user capacities. In this respect, in this work we propose a solution that starts from the principles of ABS and exploits jointly the dimensions of frequency, power and time in order to balance the trade-off between interference mitigation on the small cells and capacity degradation in the macrocells. Comparisons against the classical ABS and other existing solutions show the efficiency of the proposed scheme with improvements in the user capacity that reach up to 26% in the considered scenarios. This is achieved without significant degradation of the performance observed by small cell users.**

Keywords— Heterogeneous Networks, Cell Range Expansion, Almost Blank Subframes, enhanced Inter-cell Interference Coordination

I. INTRODUCTION

Device proliferation dominated by data hungry applications imposes a set of challenges, such as enhanced coverage and high capacities that operators and researchers need to surpass. Long Term Evolution (LTE) and LTE-Advanced (LTE-A) have been the starting point for a new era of technology evolution that can improve system performance, especially with the transition from traditional homogeneous deployments to Heterogeneous Networks (HetNets). The later combines several types of macro and small cells (e.g. picocells, femtocells) and different technologies (e.g. Wi-Fi) in order to provide better coverage in areas with high user density (Hot Spots) and allow higher data rates. However, moving to more complex deployment scenarios requires new or enhanced techniques that are compliant and can satisfy the new demands [1]. Examples include user association and interference mitigation schemes.

In the traditional homogeneous deployments, the users are connected to a cell according to the measured received signal strength (RSS) or Signal to Interference and Noise Ratio (SINR). However, in the heterogeneous deployments the transmit power of the small cells is much lower than that of the macrocell, leading to less users off-loaded from the macrocell. A solution to this problem is the introduction of the Cell Range Expansion (CRE) technique [2][3], which consists in adding a positive offset (cell bias) to the RSS or SINR measurements of the users. This results in the extension of the coverage footprint of the small cells and permits in this way more users to be off-loaded from the macrocell. However, despite the benefits brought from CRE, the users that are located in the extended area of the small cells suffer from low signal quality and are quite susceptible to interference.

In order to alleviate the interference issues imposed by the use of CRE, enhanced Inter-cell Interference Coordination techniques (eICIC) are used in LTE-A [4]. One of them is a time domain method known as Subframe Alignment, where the available subframes are partitioned into Normal and Almost Blank Subframes (ABS) [2][5]. The macrocell data transmission is limited only to the Normal subframes, while no data is transmitted during the ABS subframes (only some reference signals are sent). In this way, thanks to their reduced interference conditions, the ABS subframes can be exploited by the small cells and especially by the users that are located in the extended area.

Despite the improvements brought by ABS, it presents some drawbacks when it comes to the macrocells user capacity. Due to the silent periods of the macrocell the available resources are underutilized resulting in degradations in the achieved capacity. As such, recent works have focused on the optimization of the eICIC scheme, mainly targeting the selection of the best parameters for each scenario. In [6] the authors have studied the optimal number of ABS subframes and have exploited dynamic programming to determine the victim users and the optimal number of ABSs. A joint optimization solution for the CRE and ABS parameters based on the Lagrange dual method has been presented in [7].

To the best of our knowledge, the majority of the proposed solutions aim at reconfiguring the number of ABSs and/or the cell bias. However few works have addressed the enhancement or modification of the ABS scheme itself. In some 3GPP contributions (e.g. [8][9]) the possibility of allowing low power macrocell transmissions during the ABS subframes, denoted as Low Power ABS (LP-ABS), is studied. In [10] a performance evaluation of this scheme is presented addressing also some technical and standardization challenges. Another solution has been presented in our previous work [11] to increase the macrocell capacity, while keeping the interference generated to the small cell users in low levels. The solution considers two different situations. When the small cells are located close to the macrocell, the solution exploits the frequency and time dimensions. In turn, when the small cells are located far from the macrocell, it exploits the power and time dimensions.

Based on the above framework, in this paper we propose a new eICIC algorithm for managing ABS subframes that jointly exploits the time, frequency and power dimensions to improve the resource utilization and better compensate the trade-off between interference reduction to small cell users and capacity degradation for macrocell users. The proposed approach is compared against previous references existing in the literature to assess the benefits in terms of achieved capacity gain.

The rest of the paper is organized as follows. In Section II, the system model considered in this work is presented. Section III describes the proposed scheme. In Section IV, the simulation parameters and the numerical results are given and finally, in Section V, the most important conclusions and the targets for the future work are presented.

II. SYSTEM MODEL

We consider a heterogeneous network consisting of macro and small cells. The set of the macrocells is denoted as $i = 1,2..., M$ and the set of small cells is denoted as $k = 1,2,...,S$. A set of users U is randomly distributed in the scenario in a heterogeneous way, forming some hot spot areas with higher user density than other parts. The user-to-cell association is based on the user RSS measurements with CRE bias denoted as Δ (dB). According to the cell association, the set of users is divided into two different subsets. Subset $U_{M,i}$ contains the users connected to the *i-th* macrocell and subset $U_{S,k}$ corresponds to the users connected with the *k-th* small cell. Moreover, $U_{S,k}$ is further divided into two: $U_{CRE,k}$ is the subset of CRE users of the *k*-th small cell (i.e. the users located in the expanded region of the *k*-th small cell, so that they receive a higher RSS from the macrocell than from the small cell), and $U_{N,k}$ is the subset of normal users (i.e. those that receive a higher RSS from the small cell).

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 10 ms. 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. ABS technique is applied with μ denoting the number of ABS subframes per frame. Non-ABS subframes are denoted as Normal subframes.

The total propagation losses of user $u \in U$ in the $RB(f,t)$ 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.

The transmit power of the *k*-th small cell is $P_{TS,k}$. In turn, two possible transmit power levels, denoted as $P_{TM,i,high}$ and $P_{TM,i,low}$, are considered for the *i*-th macrocell. The selection of one or another level will be explained later on in Section III.

III. PROPOSED EICIC SOLUTION

With the introduction of the ABS scheme, the small cells user capacity can be significantly improved since the interference seen by these users is reduced. However, this comes at the cost of a decrease of the macrocells user capacity since macrocells are restricted to utilize only part of the resources, i.e. the Normal subframes. In this respect, in this work a smart mechanism is proposed that allows a more efficient use of the resources. This is achieved by allowing transmission of the macrocell in the ABS 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 and the maximum allowed transmit power. More specifically, considering the *i*-th macrocell and the small cells falling in the coverage area of this macrocell, the proposed strategy is explained in the following and illustrated in Fig. 1.

Instead of devoting to the small cells all the RBs in the ABS subframes as in the classical ABS scheme, the frequency domain is split in two areas in order to separate the transmissions. This is done by reserving a number of RBs $\varepsilon \le numRB$ in each ABS subframe, as it can be seen in Fig. 1. These reserved RBs are primarily devoted to the CRE users of the small cells, since they are the most sensitive users to the macrocell interference. This means that no macrocell transmissions are permitted during these ε RBs. Therefore, the macrocell transmissions can take place in either the Normal subframes with transmit power $P_{TM,i,high}$ or in the $(numRB - \varepsilon)$ non-reserved RBs of the ABS subframes with the restriction of a lower transmit power $P_{TM,i,low}$. In this way, the generated interference to the normal users of the small cells is kept at low levels, while we avoid having the macrocell completely silenced during an ABS subframe, resulting in an increase of the macro capacity.

Based on the above considerations, the allocation criteria can be summarized as follows, as seen in Fig. 1:

1. Small cell transmissions to the CRE users will be carried out only in the reserved RBs of the ABS subframes with $P_{TS,k}$.
2. Transmissions to the normal users will be allocated preferably in RBs of the ABS subframes (either reserved or non-reserved). However they are allowed to be performed in the RBs of the Normal subframes if there are not sufficient RBs in the ABS subframes. In all the cases the transmit power will be $P_{TS,k}$.
3. Macrocell transmissions will be allocated preferably in the RBs of the Normal subframes with $P_{TM,i,high}$. When the resources are not sufficient they can be assigned to the non-reserved RBs of the ABS subframes with $P_{TM,i,low}$.

A key factor of the proposed solution is that the number ε of reserved RBs will be reconfigured depending on the number of CRE users. In particular, in this work we assume

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

where *numCRE* is the total number of CRE users in the small cells within the coverage area of the *i*-th macrocell, α is a parameter of the algorithm that corresponds to the average number of reserved RBs per subframe required by a CRE user, and $[\cdot]$ represents the rounding operation to the nearest integer value. As such, if there are few CRE users, the reserved RBs are reduced, while as the number of CRE users increases we approach the conventional ABS strategy where the macrocell cannot transmit in any of the RBs (i.e. $\varepsilon = numRB$).

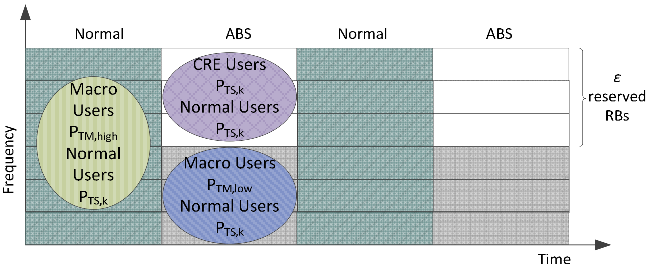

Fig. 1: User Allocation principles in the proposed Solution

The pseudo-code of the scheduling algorithms for allocating the different RBs in each frame according to the abovementioned proposed strategy are presented in Algorithm

1 and Algorithm 2 for the macrocells and the small cells, respectively. Along with the allocation criteria presented above, the user prioritization for the scheduling in the available RBs follows the principles of the Proportional Fair algorithm [12]. In particular, for each user u (where $u \in U_{M,i}$ for the scheduling at the i-th macrocell and $u \in U_{S,k}$ for the scheduling at the k-th small cell) the following priority metric is defined associated with each $RB(f,t)$:

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

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

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

In equation (3), $SINR_{u,RB(f,t)}$ is the signal to interference and noise ratio seen by the user u 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. Besides, as noted in Algorithm 1 and Algorithm 2, in order to avoid allocating a 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 $R_{u,RB}(f,t)$ (i.e. Σ_u) in the RBs allocated to this user should be below a maximum value $R_{b,max}$.

Algorithm 1: Scheduling Algorithm in the i-th macrocell

```
compute $m_{u,RB}(f,t)$ for each user $u \in U_{M,i}$ ,for all RBs
initialize $\Sigma_u=0$ for each user $u \in U_{M,i}$
for each normal subframe t                    //Normal subframes
  for (f=1;f<=numRB)
    $U_{aux}$=set of users in $U_{M,i}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
    $u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
    allocate RB(f,t) to user u* with $P_{TM,i,high}$
    $\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
  end for
end for
for each ABS subframe t                       //ABS subframes
  for (f= ε +1;f<=numRB)                      //non-reserved RBs
    $U_{aux}$=set of users in $U_{M,i}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
    $u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
    allocate RB(f,t) to user u* with $P_{TM,i,low}$
    $\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
  end for
end for
```

IV. SIMULATION RESULTS

The proposed solution has been evaluated through simulations and compared with different existing solutions. In particular, the same scenarios have been simulated for the case of the classical ABS, the LP-ABS approach of [8]-[10] and the solution of our previous work [11]. In this section we present the simulation environment, the evaluation criteria and the most important results.

A. Simulation Scenario and parameters

The simulation environment consists of a macrocell with three small cells inside its coverage area. Two scenarios with different small cell deployments are considered as seen in Fig. 2. In *scenario 1*, all the small cells are located far away from the macro base station (BS), while in *scenario 2* one of the small cells is closer to the macro BS so the small cell users are more susceptible to interference. In both cases, a total of 110 users are randomly distributed in the scenario following a uniform distribution. In addition, two Hot Spots are also considered as seen in Fig. 2. Hotspot 1 contains 20 users, while the number of users of Hotspot 2 is varied throughout the simulations.

Algorithm 2: Scheduling Algorithm in the k-th small cell

```
compute $m_{u,RB}(f,t)$ for each user $u \in U_{S,k}$ ,for all RBs
initialize $\Sigma_u=0$ for each user $u \in U_{S,k}$
for each ABS subframe t                       //ABS subframes
  for(f=1;f<= ε)                              //reserved RBs
    $U_{aux}$=set of users in $U_{CRE,k}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
    if $U_{aux} = \varnothing$
      $U_{aux}$=set of users in $U_{N,k}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
    end if
    $u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
    allocate RB(f,t) to user u* with $P_{TS,k}$
    $\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
  end for
  for (f= ε+1;f<=numRB)                       //non-reserved RBs
    $U_{aux}$=set of users in $U_{N,k}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
    $u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
    allocate RB(f,t) to user u* with $P_{TS,k}$
    $\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
  end for
end for
for each normal subframe t                    //Normal subframes
  for (f=1;f<=numRB)
    $U_{aux}$=set of users in $U_{N,k}$ with $R_{u,RB(f,t)} \geq R_{b,min}$ and $\Sigma_u \leq R_{b,max}$
    $u^* = \arg\max_{u \in U_{aux}} m_{u,RB(f,t)}$
    allocate RB(f,t) to user u* with $P_{TS,k}$
    $\Sigma_{u^*} = \Sigma_{u^*} + R_{u^*,RB(f,t)}$
  end for
end for
```

The calculation of the propagation losses of a user u with the i-th macrocell ($L_{M,u,i,RB(f,t)}$) and the k-th small cell ($L_{S,u,k,RB(f,t)}$) is carried out according to the following equation:

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

where d is the distance between user u and the cell site, S(dB) is the shadowing modelled as a Gaussian random variable with 0 mean and standard deviation σ=6 dB and F is the fast fading due to multipath, modelled as an exponential random variable with average 1 assumed independent for each RB and frame.

Moreover, the number of the reserved RBs ε is calculated according to (1) with $\alpha=2/\mu$. This value is obtained assuming that each CRE user will require on average 2 reserved RBs in total to transmit at $R_{b,max}$. Then, the number of required RBs per CRE user and per subframe will be given by $\alpha=2/\mu$. Table I presents the rest of simulation parameters.

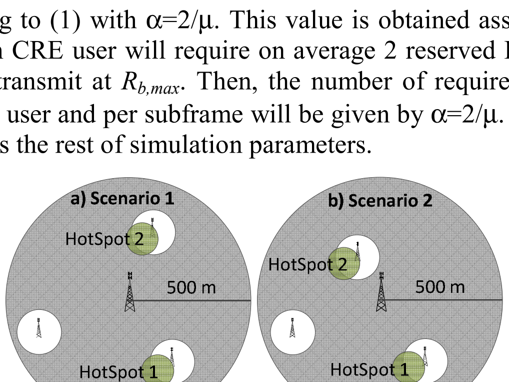

Fig. 2: Simulation Scenarios

The system performance is evaluated in terms of the average capacity per user, which is computed by averaging over all the simulated frames the capacity C_u that a user u gets in each frame according to the scheduling process. C_u is computed by aggregating the bit rate in all the RBs allocated to the user u in this frame, that is:

$$C_u = \sum_{RB(f,t)\text{ allocated to user u}} B_{RB}\log_2\left(1+SINR_{u,RB(f,t)}\right) \qquad (5)$$

The presented results for each simulation correspond to the average of 100 experiments associated with different random user distributions. Each experiment lasts 1000 frames.

B. *Reference strategies for comparison*

The proposed strategy is compared against the following approaches:

a) The classical ABS scheme 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 $P_{TM,i,high}$.

b) The LP-ABS strategy from [8]-[10], where the macrocell is allowed to transmit with lower power (i.e. $P_{TM,i,low}$) in all the RBs of the ABS subframes.

c) The solution of [11], where two different mechanisms are applied according to the small cells positions. When the small cells are far away from the macro BS, the macrocell is split into two areas (inner/outer). Then, transmissions may take place in the ABS subframes with $P_{TM,i,low}$ only for the users that belong to the inner area. In the case that the small cells are located close to the macro BS, the ABSs are split in the frequency dimension into reserved and non-reserved RBs, and the macrocells can transmit in the non-reserved area with $P_{TM,i,high}$.

In all the cases, small cell transmissions to CRE users can take place only in the ABS subframes, while transmissions to normal users can be assigned in either ABS or Normal subframes. Moreover, in order to have a fair comparison, the three reference schemes consider the same PF prioritization criteria and the $R_{b,min}$, $R_{b,max}$ constraints in the scheduling algorithm as in the proposed approach.

C. *Simulation Results*

Scenario 1: In this scenario the three small cells are located far away from the macro BS, in order to study the case where the small cell users are less susceptible to interference. In Fig. 3, the % gains in the average user capacity of the proposed solution, the LP-ABS and the solution of [11] with respect to the classical ABS scheme are presented. Results of the proposed approach are presented in solid lines, while the results of [11] and LP-ABS are presented in dashed and dotted lines, respectively. It is worth mentioning that, with the deployment in this scenario, the algorithm of [11] allows transmissions to the users of the inner cell area in the ABS subframes with $P_{TM,i,low}$.

From the figure it can be seen that the proposed solution outperforms the rest of strategies. First of all, our proposed solution achieves a gain of up to 20% when compared with the classic ABS. This results from the fact that the macrocell has more resources available for transmission, while the introduced interference to the small cells is kept in low levels. In comparison to the other two solutions, the proposed scheme performs better due to the fact that interference is seen only by the normal small cell users, while the transmissions for the CRE users, which are the most sensitive users to interference, are performed in the reserved RBs where no macrocell transmissions exist. Instead, in [11], all the small cell users (including the CRE users) receive interference from a fraction of the macrocell users (i.e. from the inner users), while in the case of the LP-ABS the interference comes from all the macrocell users to all the small cell users. It has to be noted also that the obtained gain with all the schemes with respect to the classic ABS reduces when decreasing the number of ABS subframes.

TABLE I: SIMULATION PARAMETERS

numRB	Number of RBs	25
μ	Number of ABS subframes	1 to 6
Δ	Cell Bias	6 dB
$P_{TM,i,high}$	Macro Transmit Power (high level)	29 dBm
$P_{TM,i,low}$	Macro Transmit Power (reduced level)	23 dBm
$P_{Ts,k,}$	Small cell Transmit Power	6 dBm
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

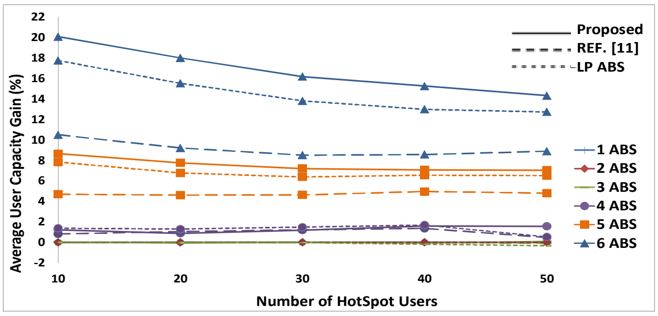

Fig. 3: Average User Capacity Gain in Scenario 1

Fig. 4 and Fig. 5 present the gain in the average capacity achieved by the macrocell and by the CRE users, respectively. As it can be seen from Fig. 4, the gain of the macrocell users is significant in the proposed solution and in LP-ABS since all the users have more resources. In the case of [11], the gain is a little bit lower because transmissions may take place in the ABS subframes only for the inner users.

Moreover, in Fig. 5 it can be noticed that, with both LP-ABS and [11], the CRE users experience stronger capacity degradations with respect to the classical ABS scheme than with the proposed approach, whose degradation is very close to 0.

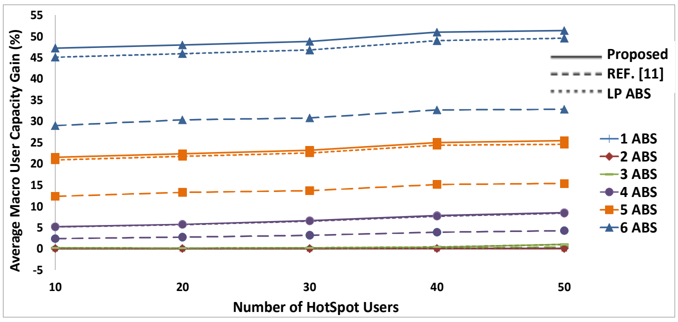

Fig. 4: Average Macro User Capacity Gain in Scenario 1

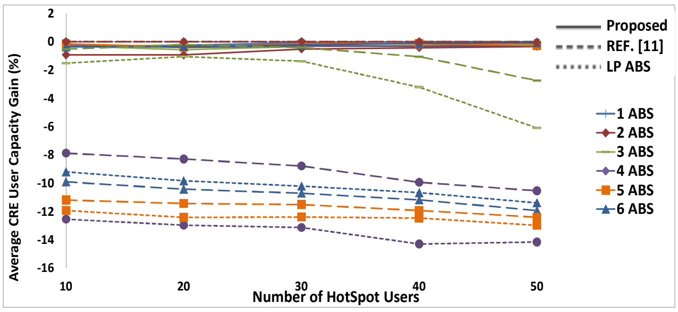

Fig. 5: Average CRE User Capacity Gain in Scenario 1

Scenario 2: In this case, one of the small cells is located close to the macro BS, so it receives more interference from the macrocell. With this topology the algorithm of [11] follows a similar approach as the proposed solution by reserving some RBs in the frequency domain for the CRE users but allowing the macrocell transmissions in the ABS subframes with $P_{TM,i,high}$.

Fig.6 presents the average user capacity gain with respect to the classic ABS for all the strategies in this scenario. In comparison to the classic ABS, the proposed solution offers a significant gain of up to 26% thanks to the better utilization of the available resources. Moreover, it outperforms the rest of the schemes. The differences with respect to [11] are small because the two solutions follow the same principles, as already referred above, but they differ in the transmit power levels. The proposed solution permits to use a lower transmit power, while in [11] the power is constant. As far as the comparison against LP-ABS, the gain of the proposed scheme results from the fact that CRE transmissions can be performed in the reserved RBs where no macrocell transmissions exist, while this is not the case of LP-ABS, where the macrocell generates a higher level of interference.

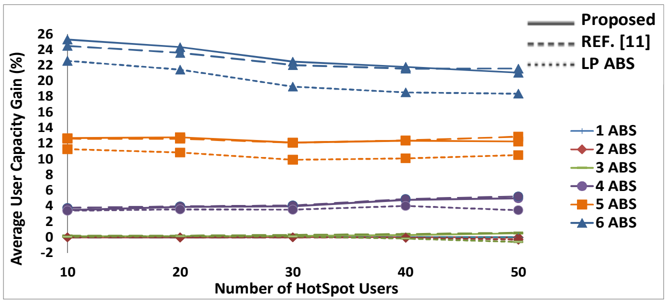

Fig. 6: Average User Capacity Gain in Scenario 2

Table II presents the capacity gain for the macrocell users and the CRE users for this scenario in the case of 6 ABS. Similar observations as in the previous scenario can be made. It can be noticed that the macrocell users' gain is quite similar for all the schemes, but in the proposed solution the CRE users are more protected from interference.

Table II: Macro and CRE Capacity Gain for 6 ABS

Hot Spot Users	Macro user GAIN (%)			CRE Gain (%)		
	Proposed	LP-ABS	[11]	Proposed	LP-ABS	[11]
10	53.81	51.15	53.94	-0.34	-8.89	-0.53
40	59.79	57.53	61.32	0.44	-11.41	-0.06

V. CONCLUSIONS

In this work we have presented a novel eICIC solution for managing ABS subframes that mitigates the interference in the small cells of a HetNet and impacts positively in the capacity of the macrocell users. The proposed scheme exploits the frequency, power and time dimensions in a combined manner in order to utilize better the available resources and increase the macrocell user capacity, while keeping the interference in the small cells in very low levels. This is achieved by reserving a number of resources in the frequency domain especially devoted to the CRE users of the small cells, and allowing macrocell transmissions in the ABS subframes with a restricted transmit power.

Through simulations and comparisons with the classical ABS and with other schemes proposed in the literature, it has been shown that the proposed solution presents higher capacity gains without convicting the small cell users to severe interference. The capacity of macrocell users is increased up to 60% with respect to the classical ABS approach, while the overall user capacity reaches gains of up to 26%.

Further improvements are envisioned to be achieved through the optimization of the involved parameters, such as the transmit power levels, the number of the reserved RBs, the number of the ABS subframes and the cell bias of CRE. Such optimization is part of our future work.

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