Energy Efficient Resource Allocation for 5G Heterogeneous Networks

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***Abstract*—This paper investigates the downlink resource allocation problem in Orthogonal Frequency Division Multiple Access (OFDMA) Heterogeneous Networks (HetNets) consisting of macrocells and small cells sharing the same frequency band. The focus of this study is to devise an energy efficient scheme that allows shared spectrum access to small cells, while ensuring a certain level of quality of service for the macro cell users. It further enable us to minimize the overall energy consumption by switching the underutilized small cells to sleep mode. To devise such a mechanism, we have used a combination of linear binary integer programming and progressive analysis based heuristic algorithm. We evaluated our proposed solution by comparing the macrocell served users performance against Reuse 1 case. Moreover, we provide an analytical comparison of the network power consumption with and without the sleep mode capabilities. It has been shown that our proposed algorithm not only reduces the overall network energy consumption but also minimizes the interference caused by smalls cells to macrocell served users.**

I. Introduction

Heterogeneous Networks (HetNets) comprising macro cells and densely deployed small cells, are considered as a promising solution for future 5G networks [1]. However, mass deployment of small cells overlayed within the area of larger cells raises challenges regarding their joint operation. Small cells (SCs) serving subscribers as part of the operators network, need to be operated in a licensed band. Since the licensed spectrum resources are expensive and scarce, operators prefer to deploy these SCs under the so-called co-channel deployment, i.e. by spatially reusing the available spectrum. As a trade-off, this sharing of the frequency band amongst the macrocell and SCs increases Inter-cell Interference (ICI) within the network which, if left unmanaged, may significantly deteriorate overall network performance [2]. ICI problem has been widely discussed in literature, with focus initially targeted at homogeneous[1] macrocell scenarios [3], [4]. However, the aforecited researches, being only designed for homogeneous scenarios, cannot perfectly fit to networks with underlaid macrocells and overlaid densely deployed SCs; the reason is that the dominant interferes for a user in the homogeneous scenario are limited and usually not as strong as in the dense HetNet scenario. Focusing on the HetNet scenarios authors in [5], [6] propose techniques to address SC to SC interference. Although SC-SC interference is a notable aspect in HetNet scenario, the degradation of performance for macrocell served users due to interference caused from SCs to macrocell users will be more critical than in case of small cell users; since there are fewer users served by SCs as compared to macrocell, SC served users are anyway allocated with more bandwidth resources. Thus, regarding the interference from SCs to macrocell users, [7]–[9] propose solutions to address interference caused by SC transmissions to macrocell users.

Our previous work in [7] addressed the interference caused by SCs to macrocell users. However, we realised that at certain extreme (high/low traffic) conditions of the network, some SCs were underutilised either due to very limited existing load or due to muting when causing high interference to macrocell users. This observation gave us the motivation to modify our previous formulation with respect to energy efficiency (EE), by including sleep mode capability to SCs.

Even though SCs have a relatively lower power consumption profile, one of the major concern in future dense deployments is the high aggregated energy consumption. Deployment of small cells, in hotspots and cell edges is beneficial for Quality of Service (QoS) as well as from EE point of view. But these gains come at the cost of deploying SCs at ideal locations, either where data requirements are high or macrocell performance is low [10]. However, it is difficult to predict the optimal locations of these nodes, and it gets even difficult to manage in case of subscriber deployed SCs. Considering the dense subscriber owned deployment of SCs, they may not be beneficial in terms of EE, since these small cells are operational at all times of the day. Even if there are no users to be served, a substantial amount of circuit energy is being drawn by these nodes. Considering the expected heavy deployment of SCs in the near future and the dynamic traffic demands, sleep modes pose a very promising solution to overcome the wastage of energy in case of low SC utilisation. A SC node, other than the *active* (i.e. full operational) mode, can be in *idle* or *sleep* mode. Since generally there are fewer users served by SCs, many SCs are not utilised most of the time and the idle mode energy gets wasted; switching the node to sleep mode significantly reduces the energy consumption. The simplest sleep mode technique, where almost all the modules of a SC are shut down is based on a fixed timer [10]. This timer is manually configured for a statistical traffic cycle, usually during few hours of night when user traffic is very low.

[1]By homogeneous networks, we indicate the networks with same size and same access technology cells.

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A drawback of such a scheme is that since the sleep mode cycle is static and only based on traffic statistics, in event of unusual activity the system performance might degrade or need to be manually reconfigured.

For this work, we utilise the umbrella macrocell to guide the SCs to change their operational state, based on the reported activity levels. We mathematically formulate the optimisation problem for this scenario, and considering the time and computational limitations of a practical network we further solve the problem based on a heuristic algorithm. The rest of this paper is organised as follows. Section II presents the system model along with mathematical formulation of the optimisation problem. Section III discusses the proposed heuristic scheme along with the pseudocode. Simulation results and obtained insights are discussed in Section IV. Finally, Section V concludes the paper.

II. System Model

We consider a system of $M+1$ cells, as depicted in Fig. 1, comprising one macrocell (identified as cell 0) and M small cells within the macrocell area. The set of SCs is defined as $\mathcal{M} = \{1, \ldots, M\}$. We assume that there are K active users in the system. We consider that each user can have only one serving node, but each cell can support multiple users; thus, $K \triangleq |\mathcal{K}| = |\mathcal{K}_0 \cup \mathcal{K}_1 \cdots \cup \mathcal{K}_M|$, where $\mathcal{K}$ denotes the set of all users in the system and $\mathcal{K}_m$ denotes the set of users served by node in cell m.

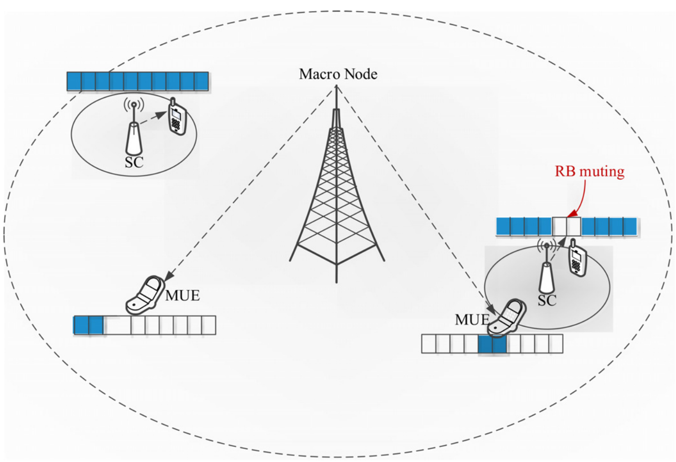

Fig. 1: System Model.

Following the binary RB allocation nature of the OFDMA systems the total system bandwidth is divided in N resource blocks (RBs) and each RB can be allocated to only one user in each cell. Macrocell node can allocate all the available RBs to its associated *macro-users* (MUE). Moreover, macrocell users are assumed to have minimum data rate requirements.

On the other hand, small cells reuse the same resources to serve their *small cell-users* (SUE) based on a resource allocation policy. We consider a central entity residing at the macrocell node which is able to collect relevant information to make resource allocation decisions and guide small cells on the resource allocation policy to be adopted.

We define binary indicator variables $\phi_{k,m,n} \in \{0,1\}$, where $\phi_{k,m,n} = 1$ when SC m serves its k^{th} assigned user in the n^{th} RB; otherwise, the RB allocation parameters take the zero value. Thus, we can define the vector containing all RB allocation parameters $\boldsymbol{\phi} = [\phi_{1,1,1} \ldots \phi_{K_M,M,N}]$, which characterizes the SCs' *RB allocation policy*. We also define the binary cell ON/OFF state indicator $\psi_m \in \{0,1\}$, where $\psi_m = 1$ indicates the active state of cell m; otherwise, in OFF state it take the zero value. Moreover, transmit power of the m^{th} small cell in the n^{th} RB is denoted by $p_{m,n} \leq P_{\max}$, where $P_{\max}$ is the maximum allowed transmission power of any small cell. Vector $\mathbf{p} = [p_{1,1} \ldots p_{M,N}]$ characterizes the small cells *power allocation policy*.

A. User SINR and Rate Modelling

The SINR of the u^{th} MUE at RB n can be given by:

$$\gamma_{u,0,n} = \frac{p_{0,n}\Gamma^{0}_{u,0,n}}{\sum_{m=1}^{M}\left(\sum_{k\in\mathcal{K}_m}\phi_{k,m,n}\right)p_{m,n}\Gamma^{m}_{u,0,n} + N_0 B}, \quad (1)$$

where $p_{0,n}$ denotes the transmit power of macrocell node at RB n, $\Gamma^{i}_{k,m,n}$ is the channel gain between base station at cell i and user k being served at cell m in RB n, N_0 is the noise power spectral density and B is the bandwidth of each RB.

Similarly, the SINR of SUE k in cell m at RB n can be given by:

$$\gamma_{k,m,n} = \frac{p_{m,n}\Gamma^{m}_{k,m,n}}{p_{0,n}\Gamma^{0}_{k,m,n} + \sum_{\substack{i=1\\ i\neq m}}^{M}\left(\sum_{l\in\mathcal{K}_i}\phi_{l,i,n}\right)p_{i,n}\Gamma^{i}_{k,m,n} + N_0 B}. \quad (2)$$

The rate of each user (SUE or MUE) can be expressed by the Shannon-Hartley Theorem as follows:

$$R_{k,m,n} = B \ \log_2\left(1 + \gamma_{k,m,n}\right). \quad (3)$$

It should be noted that although (3) does not provide a practically achievable rate, it is used as a performance indicator for comparison purposes.

B. Maximum Interference Allowance

A minimum overall data rate demand for a MUE can be translated into a minimum data rate demand at each RB, allocated to that specific MUE. Moreover, the minimum MUE demand data rate at RB n can be translated into a specific minimum required $\gamma^{\text{req}}_{u,0,n}$ SINR value [11]. Having identified the minimum SINR value and considering (1) we can find the maximum interference power $\Omega^{\max}_{u,n}$ that MUE u can tolerate in RB n from all small cell nodes to obtain this rate threshold:

$$\Omega^{\max}_{n} = \frac{p_{0,n}\Gamma^{0}_{u,0,n}}{\gamma^{\text{req}}_{u,0,n}} - N_0 B. \quad (4)$$

If the potential channel gain from any small cell m to the MUE is denoted as $\Gamma^{(m)}_{0,u,n}$, the total interference caused to it by all small cells in each RB can be given by:

$$\Omega_n^{\text{sum}} = \sum_{m=1}^{M} \left(\sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \right) p_{m,n} \Gamma_{u,0,n}^{m} = \sum_{m=1}^{M} \left(\sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \right) \omega_{u,0,n}^{m}, \tag{5}$$

where $\omega_{u,0,n}^{m} \triangleq p_{m,n}\Gamma_{u,0,n}^{m}$ can be interpreted as the interference that is caused to user u in cell 0 (macrocell) on RB n from small cell m.

C. Network Power Optimisation

The total instantaneous power of a cell can be given by the sum of circuit and the transmit power as:

$$P_m^{\text{total}} = \psi_m (P_m^{\text{circuit}} + \Delta_m . P_m^{\text{transmit}}) \tag{6}$$

where, P_m^{circuit} is the constant circuit power which is drawn if transmit node m is active and is significantly reduced if the node goes into sleep mode. P_m^{transmit} is the node's transmit power and Δ_m donates the slope of load dependent power consumption [12].

The general network power optimisation problem comprising the objective function and the imposed constraints can be formulated as follows:

$$\min_{\mathbf{p},\boldsymbol{\phi},\boldsymbol{\psi}}, \sum_{m=0}^{M} P_m^{total} \tag{7}$$

subject to:

$$\phi_{k,m,n} \in \{0,1\}, \forall k \in \mathcal{K} \setminus \mathcal{K}_0, m \in \mathcal{M}, n; \tag{7a}$$

$$\sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \in \{0,1\}, \forall m \in \mathcal{M}, n; \tag{7b}$$

$$\Omega_n^{\text{sum}} \leq \Omega_n^{\max}, \quad \forall n; \tag{7c}$$

$$\psi_m \in \{0,1\}, m \in \mathcal{M}, n; \tag{7d}$$

$$\psi_0 = 1; \tag{7e}$$

$$R_{k,m} \geq R_{k,m}^{min}, \forall m \neq 0; \tag{7f}$$

$$\sum_{n=1}^{N} \left(\sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \right) p_{m,n} \leq P_{\max}, \forall m \in \mathcal{M}; \tag{7g}$$

$$p_{m,n} \geq 0, \forall m \in \mathcal{M}, n. \tag{7h}$$

Constraint (7b) indicates that RBs are exclusively allocated to one user served by each cell pair to avoid intra-cell interference; constraint (7c) denotes the total maximum interference that a MUE served by macrocell on RB n can tolerate from all SCs in the macro area in order to satisfy its minimum rate needs; constraint (7d) indicates the ON/OFF state of the cells and constraint (7e) makes sure that the macrocell is always in active state. Constraint (7f) is the minimum required rate constraint for each user; finally, constraints (7g)-(7h) stand for the maximum and minimum transmission power constraints at each SC node. The formulated optimisation problem being extremely complex in nature is very difficult to solve in a real network with dynamically changing conditions. To address the complexity issues we devise a low complexity heuristic solution, explained in the following section.

III. Proposed Resource Allocation Schemes

The proposed Energy Consumption Aware Resource Allocation Scheme (ECA) heuristically achieves the objective expressed in the optimisation problem in (7). Although the proposed scheme is a sub-optimal solution to problem in (7), the aim behind this solution is to keep the computational complexity very low considering a practical network.

ECA scheme solves in the first step the RB allocation problem using linear binary integer programming. The objective is to guide the SCs with their respective muting parameter in $\vec{\phi}_n$, in order to satisfy the maximum interference tolerance threshold for the macrocell served UEs. This process is repeated over a shorter interval e.g in an order of milliseconds. Once the SCs are guided with their muting parameter, the algorithm analyses the possibility of switching off underutilised SCs. For this, the macrocell checks if the sum of MUEs' average date-rate demand is below a certain threshold. If so, the underutilised SCs are switched to sleep mode.

We simplify this process by comparing the number of available RBs (RB_0^{Avail}) at the macrocell (the RBs which are not being used to serve MUEs) with a minimum threshold number of RBs (RB_0^{Thres}). Now, based on the reported activity of the SCs, the ON/OFF state problem is solved in a progressive manner considering the SCs with lowest utilisation at first. Here we consider that a SC may result in a low utilisation if it has very low load (serving few users with low average data-rate requirement/constraint) or if it has a very high RB muting factor (causing high interference to macrocell users). The ON/OFF state solution is passed to the SCs, and the macrocell continuously monitors its performance over a longer time interval e.g. minutes. If a congestion (C_0=1) i.e. utilisation of RBs above certain percentage of available capacity is identified by the macrocell, it detaches the SUEs in a progressive manner prioritising the SUEs with highest average data-rate requirements. The flow diagram of the proposed algorithm is presented in Figure 2, followed by the pseudocode.

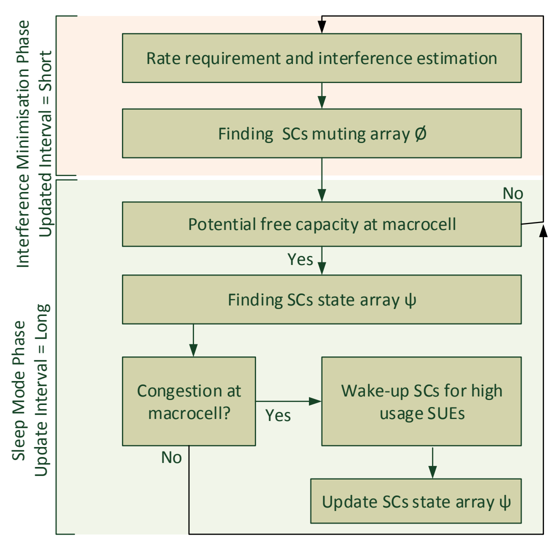

Fig. 2: Flow Diagram for ECA Scheme

Algorithm 1 Energy Consumption Aware Resource Allocation (ECA)

for $n = 1 \rightarrow N$
  Initialise : $\vec{\phi}_n = \vec{0}$
  Calculate : $\Omega_n^{\max}$,$\omega_{u,0,n}^{m}$,$R_{k,m,n}$ as in eq. 3, 4 and 5
  $\vec{\phi}_n$= *bintprog* $(\vec{R}_n,\ \vec{\omega}_{u,0,n},\ \Omega_n^{\max})$
end
Notify SCs with their respective $\phi_{m,n}$.

Small Cell Sleep Mode Phase
Analyse Available n RBs at Macrocell
if $RB_0^{\text{Avail}} > RB_0^{\text{Thres}}$
  Sort small cell utilisation $\vec{U}$ in descending order
  while $RB_0^{\text{Avail}} < RB_0^{\text{Thres}}$
    Send sleep mode activation message to SC on top of $\vec{U}$.
    Update RB_0^{Avail}, Remove top element from $\vec{U}$.
  end

Small Cell Wake-up Phase
For every SC in sleep mode **do**:
if $\sum_k RB_{k,m}^{\text{Req}} > RB_0^{\text{Avail}}$ **OR** $C_0 = 1$
  Sort $\sum_k RB_{k,m}^{\text{Req}}$ in ascending order for all m
  while $\sum_k RB_{k,m}^{\text{Req}} > RB_0^{\text{Avail}}$ **OR** $C_0 = 1$
    Send wakeup message to SC on top of the list
    Update RB_0^{Avail}
  end
end

IV. Simulation Results

In this section we show the simulation results for our proposed scheme and compare the results in terms of power consumption and users' data rate performance against the conventional schemes. Details of the simulation parameters are given in Table I.

TABLE I: LTE-Based Scenario - Simulation Parameters.

Parameter	Macro-cell	Small-cell
Number of nodes	1	15
Carrier frequency	2.1 GHz	
Bandwidth	10 MHz	
Node transmit power	43 dBm	23 dBm
Path loss model	$128.1 + 37.6 \log_{10}(d[\text{Km}])$	
UE Generation	Poison Arrival Process	
RB_0^{Thres}	15%	
Noise Figure at UE	9 dB	
Thermal noise density	-174 dBm/Hz	
Cell Radius	800m	50m
P^{circuit} [12]	120W	8.4W
Δ(slope of load dependent power consumption)	3.2	4

For the purpose of demonstrating the function of the proposed algorithm, we simulate a network with 15 SCs and a single macrocell. Number of users in the macrocell and SCs are generated using Poison Arrival Process for each snapshot. Simulations are performed for four normalised load conditions of the network (0.25, 0.50, 0.75 and 1). The value of λ for the Poison Process is selected considering the load cases in our results. We consider these four variations in network loads to analyse our algorithm at different times of the day [13]. Using Monte-Carlo simulations, 1000 snap shots are generated for each load case and results were averaged.

The operation of the algorithm is depicted in Figure 3 where a deployment snap shot is illustrated. The blue rings show the active SCs, whereas the green rings show the SCs which are switched to sleep mode and their SUEs are being served by the macrocell. If we consider for example SCs '2' and '13', both of them are switched to sleep mode and we can observe that they have a some MUEs (red dots) in their vicinity. The dominant interference to these MUEs causes muting of resources at the SCs. In return due the low utilisation of these SCs and the available capacity at the macrocell, the UEs of these SCs are handovered to the the macrocell and SCs '2' and '13' are switched to sleep mode. This will usually happen at the low load times of the day. Sleeping SCs might be waked-up in case there is a congestion at the macrocell or in case of increase in network load. If for example all the SUEs have similar data rate requirements, then SC '4' would be waked up first, as it has more number of SUEs.

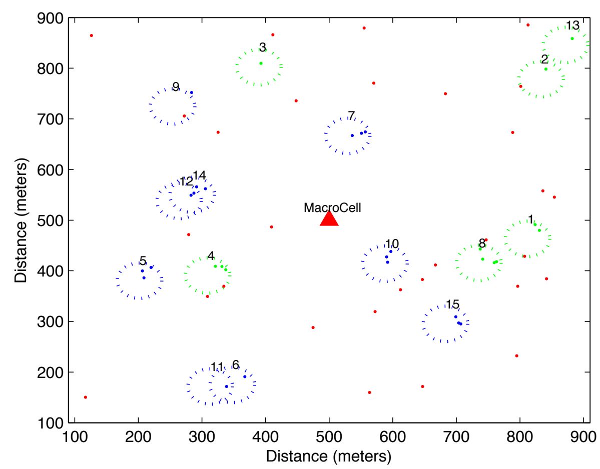

Fig. 3: Snapshot of the network with normalised load = 0.5. Red dots indicate the MUEs and blue dots indicate SUEs. Blue rings indicate the active SCs and green rings indicate SCs in sleep mode.

The Cumulative Distribution Function (CDF) for the data rates of MUEs is presented in Figure 4. We compare the performance of our proposed ECA scheme with Reuse-1 scheme (where all nodes transmit at the same frequency resources). It is evident from the figure that in case of Reuse-1 up to 20% of the users are in outage (below the required data rate mark, as indicated in the figure). This is due to the strong interference from the neighbouring SCs serving their users on the same resources. However, in case of ECA scheme, this inter-tier interference is minimised and nearly all the users are safe guarded from outage. This is made possible by muting some of the SCs at certain RBs where the victim MUEs were being served.

The proposed ECA scheme along with successfully safe-guarding the victim MUEs present in the vicinity of SCs, also maximises the energy efficiency of the network. The energy consumption comparison between ECA scheme and a conventional scheme with no sleep mode savings is presented in Figure 5. This comparison is shown for the four different considered load states of the network. This comparison for different load conditions is shown with the help of bar graphs and the y-axis of Figure 5 indicates the sum of total power consumption (circuit and load dependent transmit power) of all transmit nodes. The horizontal line in the middle of the plot indicates the constant circuit power of the macrocell which is fixed for all cases. The remaining top portion of the bars indicates the sum of macrocell's load dependent transmit power plus the circuit and transmit power of all the active SCs. The true potential of ECA scheme can be clearly seen for low to medium network load conditions. This is due to the fact that in low traffic conditions, the macrocell has unused capacity which can be successfully used to serve SUE of underutilised SCs. The energy saving gains come from switching off the circuitry of the SCs but as a trade-off the load dependent transmit power of the macrocell is slightly increased. However, upto 23% saving in total network power consumption can be achieved using ECA in these traffic conditions.

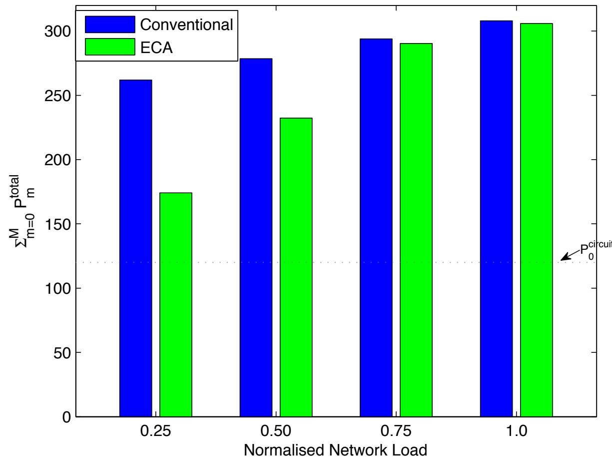

Fig. 5: Total power consumption for various network load conditions.

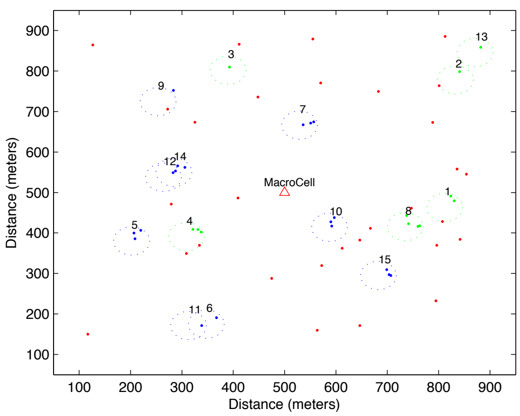

Fig. 4: CDF plot for MUE data rates

V. Conclusions

In this paper, we have proposed an energy efficient solution that not minimizes the overall network energy consumption but also address the inter-tier interference problem in a LTE HetNets environment. In our study, we formulate the mathematical optimisation problem taking into account the computational complexity limitation of a practical network. Furthermore, we have proposed a heuristic energy efficient small cell resource allocation algorithm. Our simulation results clearly indicate that nearly all macrocell served users were protected from neighbouring small cell inter-tier interference in comparison to Reuse-1 case. In addition, during the low traffic condition, the proposed mechanism has shown to reduce a significant amount of network energy by switching the underutilized cells to sleep mode.

Acknowledgement

This work was made possible by NPRP grant No. 5-1047-2437 from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors. More information about this project can be found at www.qson.org.

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