A Hybrid Algorithm for Optimization of Base Station Power Consumption and Throughput Improvement

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Abstract—The heterogeneous network (HetNet) which consists of several small cell base stations (BSs) and an overlaid macro cell BS is a promising solution to accomplish very high data rate and energy-efficient communication. The design of energy-efficient mechanisms and radio resource allocation among BSs is an important issue in HetNet. There are a variety of ON/OFF switching algorithms for BSs in the literature, however, none of these algorithms jointly consider the resource allocation problem. In this paper, we propose a hybrid interference-aware channel segregation based dynamic channel assignment (IACS-DCA) and BS sleep mode algorithm. This algorithm helps to mitigate the co-channel interference (CCI), experienced by user equipments (UEs). Simulation results show that by applying the proposed IACS-DCA approach along with a game-theoretic based algorithm for intelligent BSs ON/OFF switching, higher energy-efficiency can be achieved compared to the conventional approaches.

Index Terms—heterogeneous network; energy-efficiency; game theory; dynamic channel assignment; channel segregation.

I. INTRODUCTION

The demand for wireless resources has grown exponentially due to the large number of wireless terminals. This growth increases the load on wireless networks and leads to an increased energy consumption [1]. Hence, developing energy-efficient mechanisms and resource allocation in wireless networks are attracting much attention [1], [2]. The heterogeneous network (HetNet) which employs a set of small cell base stations (BSs), is inherently capable of improving the energy-efficiency (EE) [3] of the system, thanks to reduced pathloss. However, due to proximity of BSs, co-channel interference (CCI) may significantly affect the system performance. Therefore, CCI management will be a challenging task for next generation dense HetNets.

Existing literature has studied a number of problems related to EE in HetNet, such as BS placement, load balancing, power control, and dynamic BS sleep-wake mechanism [4]–[6]. Although these studies provide good insights into improving EE,

they all rely on a central controller which gathers all network information and makes all decisions. In [7], a distributed energy-efficient algorithm is proposed in which each BS selects ON/OFF strategies based on the current traffic load and network environment, using a game-theoretic approach. It is shown that the proposed algorithm in [7] improves the EE and reduces the overall load in the system comparable to conventional approaches even in a distributed manner.

The available resources in wireless communications, i.e., channels in frequency, time and space dimensions, is limited. Hence, the same channel needs to be reused among BSs in the network and the CCI limits the network capacity. To reuse the channels effectively, dynamic channel assignment (DCA) has been studied extensively in the literature [8]–[11]. Recently, we proposed an interference-aware channel segregation (CS) based DCA (IACS-DCA) [12], in which each BS periodically monitors the CCI environment and computes the moving average CCI powers (obtained from past CCI measurements) of all available channels. Each BS has channel-priority table, in which the channels are listed with the descending priority order (i.e., increasing order of CCI power). BS selects the best channel having the lowest average CCI power. It is shown that the proposed IACS-DCA can form a channel reuse pattern with low CCI which adapts to BS distribution [13].

In this paper, we propose a modified IACS-DCA approach, which considers the CCI environment experienced at user equipments (UEs) in the HetNet, combined with a learning game-theoretic algorithm for BSs ON/OFF switching similar to [7]. According to the network conditions (e.g., power control, UE location and BSs' ON/OFF switching pattern), CCI experienced at UEs varies over time and channel allocation should cope with this changing environment. In the proposed IACS-DCA scheme, each UE informs its corresponding BS about its channel-priority information and BSs select the best channel by analyzing such information. We show by computer simulation that the proposed IACS-DCA/sleep mode scheme can effectively manage the CCI and significantly improve the spectral efficiency (SE) of HetNet. The EE condition of the proposed algorithm is still kept at an acceptable level comparable to the only sleep mode algorithm in [7]. Another notable characteristic of the proposed scheme is that both IACS-DCA and sleep mode modules are executed in a fully
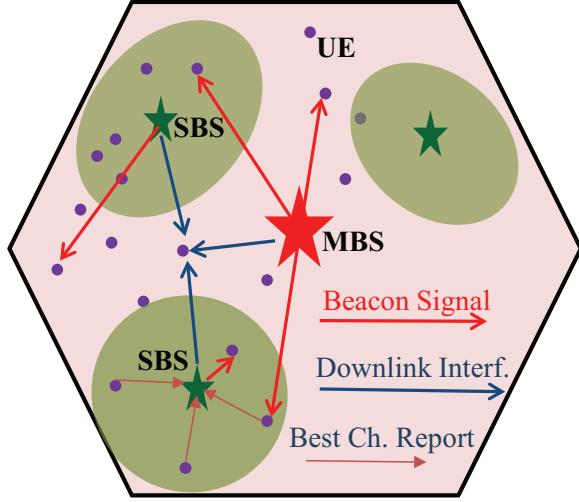
Fig. 1. System model.

distributed manner at each BS, without information exchange between BSs.

The remainder of this paper is organized as follows. In Section II, system model is presented along with the power, signal-to-interference-plus-noise power ratio (SINR), load, and cost expressions. Section III discusses different steps of our proposed algorithm, Section IV provides the simulation results and the evaluation of our algorithm, and finally, Section V concludes the paper.

II. SYSTEM MODEL

We focus on downlink transmission in HetNet. Fig. 1 shows the system model, which consists of a set of BSs, $\mathcal{S} = \{1, ..., s, ..., S\}$. We assume only one macro base station (MBS), $s = 1$, which encompasses a variable number of small BSs (SBSs), $\mathcal{S} = \{2, ..., s, ..., S\}$. A total number of X users, $\mathbb{X} = \{1, ..., x, ..., X\}$ are available in the system.

Power consumption of sth BS, BS(s), at time t is given by:

$$P_s^{\text{All}}(t) = \frac{P_s(t)}{\eta\alpha(1 - \alpha_{\text{feed}})} + P_s^{\text{Back}} + P_s^{\text{Idle}} \quad (1)$$

with

$$\alpha = (1 - \alpha_{DC})(1 - \alpha_{\text{main}})(1 - \alpha_{\text{cool}}) \quad (2)$$

and

$$P_s^{\text{Idle}} = \frac{P_{\text{radio}} + P_{\text{base}}}{\alpha}, \quad (3)$$

where $P_s(t)$ is the transmission power, η is efficiency of power amplifier, P_s^{Back} is the power consumption in backhaul, P_s^{Idle} is the power consumption in OFF mode. α_{feed}, α_{DC}, α_{main} and α_{cool} represent respectively the loss fractions of feeder, AC-DC conversion, main supply and cooler system. P_{radio} and P_{base} are the power consumption of radio frequency and baseband units, respectively.

We assume a total of C available frequency channels, $\mathfrak{C} = \{1, ..., c, ..., C\}$. Each channel uses OFDMA with N_c subcarriers. A frequency-selective block Rayleigh fading channel is considered which is composed of Q distinct paths.

The impulse response of the propagation channel at time t is modeled according to:

$$h(\tau; t) = \sum_{q=0}^{Q-1} h_q(t)\delta(\tau - \tau_q) , \quad (4)$$

where $h_q(t)$ and τ_q denote the time-varying complex-valued path gain with $E[\sum_{q=0}^{Q-1} |h_q(t)|^2] = 1$ ($E[.]$ denotes the ensemble average operation) and the time delay of the qth path, respectively.

A. SINR Expression

The downlink CCI experienced at xth UE connected to sth BS, UE_s^x, comes from the co-channel BSs using the same $c(s)$th channel and is expressed by:

$$I_{\text{UE}_s^x}(t) = \sum_{\substack{s' \in \text{BSG}(c(s)) \\ s' \neq s}} P_{s'}(t) \cdot \xi_{\text{UE}_s^x, \text{BS}(s')}$$

$$\times \sum_{k' \in N_s^x} \left| H_{\text{UE}_s^x, \text{BS}(s')}(t; k', c(s)) \right|^2 \quad (5)$$

where $\text{BSG}(c(s))$ denotes the BS group which uses the same $c(s)$th channel, $P_{s'}(t)$ is the transmit power of BS(s'). $\xi_{\text{UE}_s^x, \text{BS}(s')}$ is the path loss between UE_s^x and BS(s') and $H_{\text{UE}_s^x, \text{BS}(s')}(t; k, c(s))$ is obtained by the Fourier transform of the channel impulse response between UE_s^x and BS(s') at time t. N_s^x is the set of subcarriers assign by BS(s) to UE_s^x. Here, we do not consider any optimal subcarrier allocation for the OFDMA system. Subcarriers are divided equally and sequentially between UEs connected to each BS and we assume $N_c \gg X_s$, where X_s is the total number of UEs connected to BS(s). The downlink instantaneous SINR $\lambda_{\text{UE}_s^x}$ experienced at UE_s^x's antenna is given by

$$\lambda_{\text{UE}_s^x}(t) =$$
$$\frac{P_{s'}(t)\xi_{\text{UE}_s^x, \text{BS}(s')} \sum_{k' \in N_s^x} \left| H_{\text{UE}_s^x, \text{BS}(s)}(t; k', c(s)) \right|^2}{I_{\text{UE}_s^x}(t) + N_s^x N_0} \quad (6)$$

where N_0 is the noise power.

B. Load and Cost Function Expressions

We assume that UEs have different QoS requirements, i.e., they have different packet arrival rates and mean packet sizes. We define the instantaneous load density of each BS as the summation of the loads of all individual UEs connected to it according to:

$$\nu_s(t) = \sum_{x=1}^{X_s} \frac{\gamma_s^x}{\mu_s^x \omega' \log_2(1 + \lambda_{\text{UE}_s^x}(t))}, \quad (7)$$

where γ_s^x and μ_s^x are the packet arrival rate and mean packet size of xth UE connected to sth BS, $\omega' = \omega/C$ is the bandwidth of each BS and ω is the total system bandwidth. The load of each BS is inversely related to the throughput it provides for the UEs in its service. The averaged value of load, $\hat{v}_s(t)$, is calculated as:

$$\hat{v}_s(t) = \hat{v}_s(t-1) + l(t)(v_s(t-1) - \hat{v}_s(t-1)) , \quad (8)$$

where $l(t)$ is the learning rate. In order to ensure system stability, $l(t)$ is chosen such that the load averaging is sufficiently slower than UE association process.

A cost function similar to [7] is considered for each BS which tries to capture both load and energy consumption. The cost function for sth BS is defined by:

$$\Psi_s(t) = \varphi_s \frac{P_s^{\text{All}}(t)}{P_s^{Max}} + \psi_s \nu_s(t), \quad \varphi_s, \psi_s > 0 \tag{9}$$

where P_s^{Max} is the maximum allowed transmission power for BSs in the system, φ_s and ψ_s are weighting parameters which define the impact of energy and load, respectively.

III. PROPOSED ALGORITHM

Our goal is to design a fully distributed solution which can minimize the cost function in (9) for all BSs. The proposed algorithm is summarized in Algorithm 1.

Algorithm 1 : Proposed algorithm.

1: **Input:** $\mathcal{C}(s,t), \hat{u}_{s,i}(t), \hat{r}_{s,i}(t), p_{s,i}(t)$
2: **Output:** $a_s(t+1), \mathcal{A}(x, t+1)$
3: **Initialization:** $\mathcal{S} = \{1, ..., S\}; \mathcal{X} = \{1, ..., X_s\};$
  $\mathfrak{C} = \{1, ..., C\}; \Phi_c^s \in [0, X_s]; t = 0$
4: **while do**
5:   $t \leftarrow t - 1,$
6:   **for** $\forall s \in \mathcal{S}$ **do**
7:     Find $a_s(t) = f(p_{s,i}(t-1)),$
8:   **end for**
9:   Beacon signal transmission
10:   and load advertising, $\hat{v}_s(t)$, (8)
11:   **for** $\forall x \in \mathcal{X}$ **do**
12:     **if** $(x \in \mathcal{W}) \vee (x \in \mathcal{O})$ **then**
13:       Find $\mathcal{A}(x,t)$, (11)
14:     **end if**
15:   **end for**
16:   **for** $\forall s \in \mathcal{S}$ **do**
17:     **for** $\forall x \in \mathcal{X}$ **do**
18:       **for** $\forall c \in \mathfrak{C}$ **do**
19:         CCI power measurement, $I_{\text{UE}_s^x}(t;c)$, (5)
20:         Ave. power computation, $\bar{I}_{\text{UE}_s^x}(t;c)$, (12)
21:       **end for**
22:       Updating UEs' Table, (Fig. 2)
23:       UE's selected channel, $\mathcal{C}(\text{UE}_s^x, t)$, (13)
24:     **end for**
25:     **for** $\forall x \in \mathcal{X}$ **do**
26:       **for** $\forall c \in \mathfrak{C}$ **do**
27:         **if** $c = \mathcal{C}(\text{UE}_s^x, t)$ **then**
28:           $\Phi_c^s \leftarrow \Phi_c^s + 1,$
29:         **end if**
30:       **end for**
31:     **end for**
32:     BS's selected channel $\mathbb{C}(s,t) = \underset{c \in \mathfrak{C}}{\arg \max}\ \Phi_c^s$
33:   **end for**
34:   Updating instantaneous values, $v_s(t), \Psi_s(t)$, (7), (9)
35:   Updating $\hat{u}_{s,i}(t), \hat{r}_{s,i}(t), p_{s,i}(t)$, (14), (15), (16)
36: **end while**

A. Strategy Selection and Beacon Transmission

In the first step of the algorithm, BSs decide their action, i.e. OFF/ON mode. A non-cooperative game is used to design the decision process. In this game, the players are the BSs, strategies are different power levels chosen by BSs and the utility function of each BS is defined according to, $u_s(t) = -\Psi_s(t)$. In this paper, we use variable i to refer to each strategy and $a_s(t)$ captures the strategy selected by sth BS at time t. Each BS selects its action, $a_s(t)$, at time t based on a probability distribution, $p_{s,i}(t - 1)$, associated with each action, i.e., $p_{s,i}(t-1)$ is a mixed strategy. Assuming f as a probabilistic mapping function, $a_s(t)$ is given by $a_s(t) = f(p_{s,i}(t-1))$, where $a_s(t) \in i = \{1, ..., 4\}$. Each strategy i introduces the transmission power level, which is defined in terms of the transmission power level, $\zeta_s(t)$, and for time t is given by:

$$P_s(t) = \zeta_s(t) P_s^{\text{Max}}. \tag{10}$$

Table I shows the selected transmission power level for different strategies. Please note that MBS can only select two strategies, $i = 1$ and $i = 4$, whereas SBSs can select all four available strategies. After strategy selection, each BS periodically broadcasts the beacon signal on the selected channel along with its load estimate.

TABLE I
TRANSMISSION POWER LEVELS

Strategy Identification Number (i)	Transmission Power Level ($\zeta_s(t)$)
1	0
2	1/3
3	2/3
4	1

B. UE Association

If the UE belongs to the set of recently slept BSs, $\mathcal{W}$, or if it belongs to the set of UEs which have dropped due to overload, $\mathcal{O}$, or if the UE has newly joined the network, then it should be assigned to a new BS. In order to connect to a new BS, UEs receive the load estimate of all BSs through the beacon signal and choose the BS to which they want to connect by evaluating an association function. This association function is based on two metrics, i.e., the received signal power and the load condition of each BS. The reason to choose two metrics is to ensure a minimum required QoS for UEs and at the same time to prevent overloading of BSs. The UE's association criteria is formulated according to:

$$\mathcal{A}(x,t) = \underset{s \in S}{\arg \max} \left\{ \hat{v}_s(t)^{-\varepsilon} P_s(t) \cdot \xi_{\text{UE}_s^x, \text{BS}(s')} \right.$$
$$\left. \times \sum_{k=1}^{N_c} \left| H_{\text{UE}^x, \text{BS}(s)}(t; k, c(s)) \right|^2 \right\}, \tag{11}$$

where ε is a coefficient, which indicates the impact of each BS's traffic load.

C. Channel Selection

We use the first order filtering to compute the average CCI power received at each UE. The average CCI power, $\bar{I}_{\mathrm{UE}_s^x}(t;c)$, computed at xth UE connected to sth BS on the cth channel at time t is given by

$$\bar{I}_{\mathrm{UE}_s^x}(t;c) = (1-\beta) \cdot I_{\mathrm{UE}_s^x}(t;c) + \beta \cdot \bar{I}_{\mathrm{UE}_s^x}(t-1;c), \quad (12)$$

where $0 < \beta < 1$ denotes the forgetting factor. Using the average CCI powers on all available channels, the CCI table is updated for all available channels ($c = 1 \sim C$). Later, each UE selects the channel, having the lowest CCI power according to:

$$\mathcal{C}(\mathrm{UE}_s^x, t) = \arg\min_{c \in \mathfrak{C}} \bar{I}_{\mathrm{UE}_s^x}(t;c), \quad (13)$$

which is used until the next CCI table updating time t+1. The averaging interval of the first order filtering is given as $1/(1-\beta)$. If a too small β is used, averaging is not enough and the measured average CCI power varies like the instantaneous CCI power. Therefore, the channel reuse pattern varies at every CCI table updating time. Hence, $\beta \approx 1$ is recommended [13]. In this paper, β=0.95 is used for the computer simulation.

After all UEs report their first priority channel to their corresponding BS, the BS updates its look-up table accordingly, as shown in Fig. 2. Based on this table, BS chooses the channel which is reported by most UEs, $\mathbb{C}(s,t)$.

D. Mixed Strategy Update

Utility estimation, $\hat{u}_{s,i}(t+1)$, regret, $\hat{r}_{s,i}(t+1)$ and probability distribution, $p_{s,i}(t+1)$ of ith strategy for sth BS at time
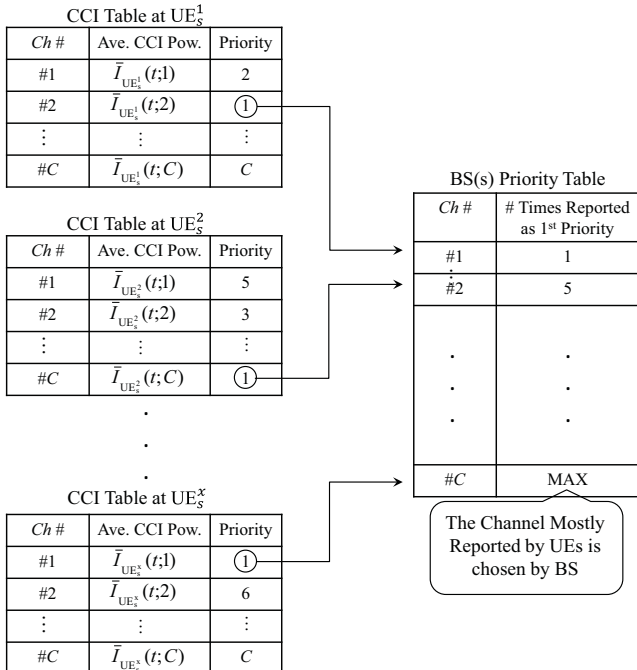

Fig. 2. Mechanism for updating priority tables.

Parameter	Value
Network	
Noise Variance, N_0	-174dBm/Hz
Arrival Rate, γ_s^x / μ_s^x	180kbps
MBS	
Max. Trans. Power, P_s^{Max}	46dBm
Min. MBS-SBS Distance (m)	75
Min. MBS-UE Distance (m)	35
SBS	
Max. Trans. Power, P_s^{Max}	30dBm
Min. SBS-SBS Distance (m)	40
Min. SBS-UE Distance (m)	10
Path loss (d:distance between UE and BS) (unit: dB)	
UE - MBS, $\xi_{\mathrm{UE,MBS}}$	15.3+37.6log$_{10}$(d)
UE - SBS, $\xi_{\mathrm{UE,SBS}}$	27.9+37.6log$_{10}$(d)
Learning Parameters	
Boltzmann temperature, σ_s	10
Weighting Parameters, φ_s, ψ_s	10, 5

$t+1$ are given by

$$\hat{u}_{s,i}(t+1) = \hat{u}_{s,i}(t) + c_b(t) \cdot \mathbf{1}(t) \cdot (u_s(t) - \hat{u}_{s,i}(t))$$
$$\hat{r}_{s,i}(t+1) = \hat{r}_{s,i}(t) + d_s(t+1)\,(\hat{u}_{s,i}(t) - u_s(t) - \hat{r}_{s,i}(t))$$
$$p_{s,i}(t+1) = p_{s,i}(t) + e_s(t+1)\,(G_{s,i}(\hat{r}_{s,i}(t)) - p_{s,i}(t)) \quad (14)$$

with

$$\mathbf{1}(t) = \begin{cases} 1 & (if\ a_s(t+1) = a_s(t)) \\ 0 & (if\ a_s(t+1) \neq a_s(t)) \end{cases} \quad (15)$$

and

$$G_{s,i}(\hat{r}_{s,i}(t)) = \frac{\exp\left(\sigma_s \hat{r}_{s,i}(t)\right)}{\sum_{i' \in A_s} \exp\left(\sigma_s \hat{r}_{s,i'}(t)\right)}, \quad (16)$$

where $G_{s,i}(\hat{r}_{s,i}(t))$ is the Boltzmann-Gibbs (BG) distribution, which is used to encourage those played actions with lower regrets and discourage actions with higher regrets. In (14), σ_s is the temperature parameter. For further information on BG distribution and its role in this game to reach the equilibrium (please refer to [14]). $c_b(t)$, $d_b(t)$ and $e_b(t)$ are learning rates which decay inversely proportional to time and should meet the following conditions:

$$\lim_{t \to \infty} \sum_{m=1}^{t} c_s(m) = +\infty, \quad \lim_{t \to \infty} \sum_{m=1}^{t} d_s(m) = +\infty,$$
$$\lim_{t \to \infty} \sum_{m=1}^{t} e_s(m) = +\infty, \quad \lim_{t \to \infty} \sum_{m=1}^{t} c_s^2(m) < +\infty,$$
$$\lim_{t \to \infty} \sum_{m=1}^{t} d_s^2(m) < +\infty, \quad \lim_{t \to \infty} \sum_{m=1}^{t} e_s^2(m) < +\infty,$$
$$\lim_{t \to \infty} \frac{d_s(t)}{c_s(t)} = 0, \quad \lim_{t \to \infty} \frac{e_s(t)}{d_s(t)} = 0. \quad (17)$$

IV. COMPUTER SIMULATION

We simulate s scenario similar to Fig. 1, where a MBS is collocated with several SBSs. Simulation parameters are summarized in Table II. Two benchmarks are considered for comparison purposes. First is a baseline approach, in which all BSs are always on. Second is the same Baseline combined with the CS at UEs and third is the energy-efficient ON/OFF switching algorithm proposed in [7].
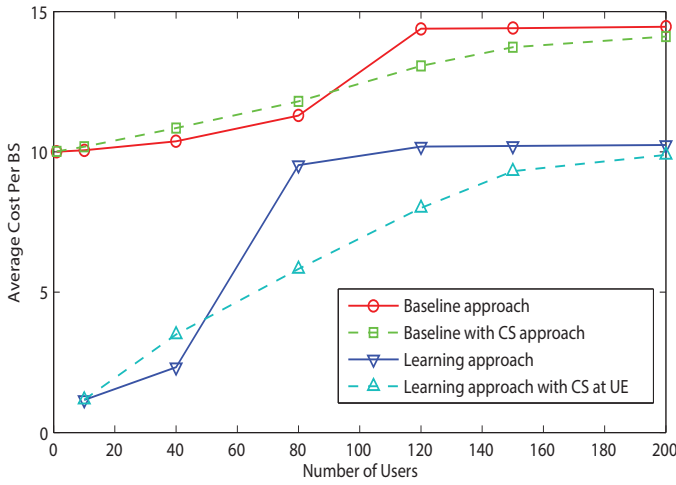
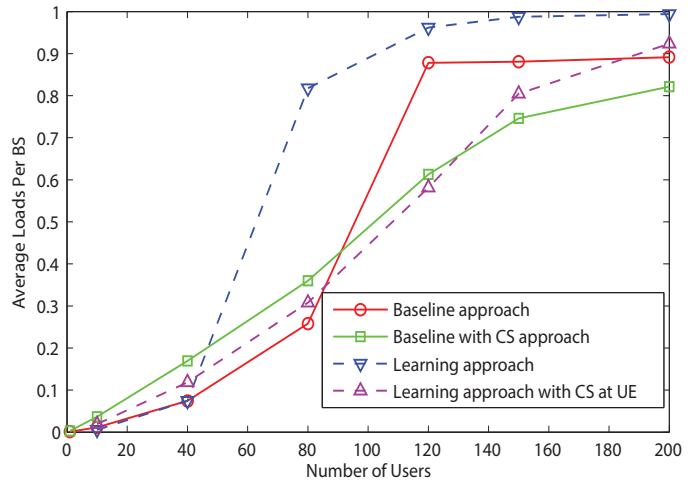Fig. 3. Average cost per BS for different total number of UEs in the system and $S = 20$ BSs and $C = 4$.

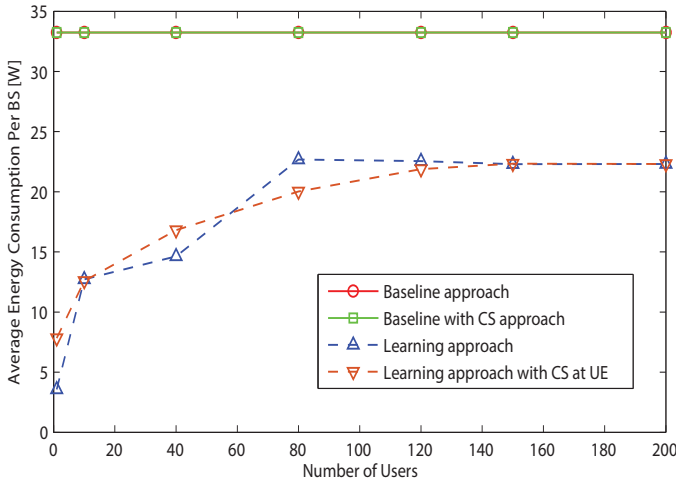Fig. 5. Average load per BS for different total number of UEs in the system and $S = 20$ BSs and $C = 4$.

Fig. 4. Average energy consumption per BS for different total number of UEs in the system and $S = 20$ BSs and $C = 4$.
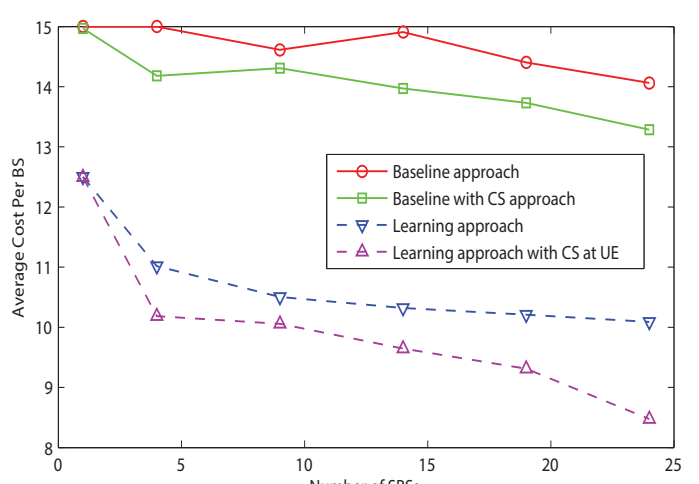

Fig. 6. Average cost per BS for different number of SBSs and $X = 150$ UEs and $C = 4$.

Fig. 3 plots average cost per BS for different number of UEs with $S = 20$ BSs and $C = 4$. For comparison, the proposed method, i.e., the learning algorithm combined with a CS approach at UEs, is compared with the three benchmark. We observe that when the number of UEs is low ($X < 40$), the proposed algorithm's performance is almost the same as the only learning algorithm in [7]. However, for higher number of UEs, the performance of the proposed algorithm is the best among the other methods. This shows the effectiveness of the IACS-DCA algorithm in mitigating the total interference in the system, which indirectly contributes to BS load reduction and improves the cost.

Fig. 4 plots the average energy consumption per BS for different number of UEs with $S = 20$ BSs and $C = 4$. It is observed that the approaches based on ON/OFF switching significantly outperform the baseline algorithms and yield at least 30% improvement in terms of average energy consumption. However, the proposed approach and the one in [7] have identical performance, with the proposed one slightly better in higher number of UEs ($X > 60$).

Fig. 5 plots average load per BS for different number of UEs with $S = 20$ BSs and $C = 4$. We can see that the proposed algorithm has similar performance compared to baseline algorithm with CS. However, it has considerably better performance compared to only learning algorithm in [7]. Please note that due to the inverse relation of system load and throughput (as shown in equation (7)), in this work lower load implies a higher system throughput and consequently higher SE. Comparing plots in Fig. 4 and Fig. 5, proves that combining the ON/OFF switching with the proposed CS method, not only improves the EE, but also increases the system SE to a great extent.

Finally, Fig. 6 illustrates the average cost per BS for different number of BS with $X = 150$ UEs and $C = 4$. Again we can see that the proposed algorithm has the best performance among the other approaches. Specifically, the gain in performance gap increases as the number of BS increase. This promising result proves the effectiveness of our method for dense scenarios.

V. Conclusion

In this paper, we proposed a joint ON/OFF switching and dynamic channel allocation algorithm which can significantly improve the average throughput. A non-cooperative game-theoretic approach was used to design the base station (BS) ON/OFF switching problem. Later, all the user equipments (UEs) connected to each BS prioritises the available channels based on their level of interference and chooses the one with the least averaged received interference. The chosen channel is reported to BS and then BS chooses the channel which was mostly reported. The algorithm is fully distributed and base stations do not need to exchange any information. The proposed algorithm shows a comparable performance with a benchmark from energy-efficiency point of view, with slight improvement in dense scenarios. However, it significantly outperforms the benchmark in terms of average system load, in dense small cell deployment scenarios.

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