Inter-Cell Interference Coordination for Highly Mobile Users in LTE-Advanced Systems

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***Abstract*— How good is the performance of the existing Inter-Cell Interference Coordination (ICIC) schemes when dealing with users moving at high speeds? In this paper, we evaluate a number of existing schemes under high user mobility conditions. Then, we propose a dynamic decentralized ICIC scheme that requires no apriori frequency planning. The proposed scheme minimizes the amount of data needs to be exchanged among base stations. The scheme uses the *Harmony Search (HS) algorithm* in order to rapidly generate a more accurate User-to-Channel allocation matrix to cope with high user mobility. We also propose power control and channel restriction strategies to minimize the power consumption and inter-cell interference. A key advantage in the proposed scheme is that its computations are independent of the number of users and cells in the network. Accordingly, it can be deployed in large networks with large number of users. Extensive simulations demonstrate that, with a slight degradation in fairness, the proposed scheme provides 18% throughput improvements to edge users without penalizing other users. In addition, the use of the power control and restriction strategies has led to a 22% reduction in power consumption.**

Keywords-LTE-Adv; ICIC; Harmony Search; High Mobility

I. INTRODUCTION

In 3GPP Long Term Evolution (LTE) systems, downlink transmission is based on Orthogonal Frequency Division Multiple Access (OFDMA). By orthogonal allocation of the OFDMA sub-carriers, intra-cell interference can be avoided. However, inter-cell interference (ICI) still presents a challenge that considerably limits the system performance and seriously affects the throughput of edge user equipments (UEs). Inter-cell interference coordination (ICIC) has been investigated as a key technology to alleviate the overall impact of ICI to improve system performance and increase edge-UEs' bit rates.

High-speed mobility of UEs in LTE systems (350km/h [1]) leads to large channel variations and continuous changing traffic distribution. This poses a real challenge when coupled with the requirements of supporting high transmission rates (300Mbps [1]). *Dynamic* ICIC schemes have emerged as a more efficient and realistic solution as opposed to the conventional static schemes. However, channel assignment problem in dynamic ICIC schemes is known to be NP-hard [2]. Accordingly, several heuristics have been proposed to solve the problem in a computational efficient manner, such as: game theory [3], integer programming [4], graph coloring [2], water filling [5], and genetic algorithms [2].

In this paper, we propose a novel dynamic decentralized ICIC scheme based on the concept of Harmony Search (HS) algorithm [6]. The proposed scheme does not require a centralized controller and only makes use of minimum amount of information exchange between eNBs. To support deployment in large networks, the proposed scheme computations are independent of the number of cells and users in the system. To the best of our knowledge, this is the first time to adopt the notion of HS in solving the channel allocation problem in the LTE-Advanced systems. Results reported in the literature show that the HS provides fast and better quality solutions compared to other optimization algorithms [7].

II. RELATED WORK

This section presents a brief overview of some recent dynamic schemes. Interested readers can refer to a comprehensive survey of various ICIC schemes in [8].

In [9], M. Rahman *et al.* proposed a scheme that shares the computations between a central entity and eNBs. Each eNB creates a wish-list of RBs to be restricted in its neighboring cells. The central entity solves the restriction requests for all eNBs and returns a decision to eNBs to apply locally. The scheme is dependent on number of users, coordinated cells, and RBs requested to be restricted. This limits the usability of this scheme to only small networks.

In [10], D. Kimura *et al.* proposed a distributed dynamic ICIC scheme where cell-center bands dynamically adapt (shrink/expand) depending on user behavior, cell load, and interference situation. In this scheme, no central controller is used and only communication between eNBs is required. However, the scheme suffers from the "fake" unavailability of edge-RBs, as each eNB can only selects a pre-determined number of RBs as edge-bands regardless the number of edge-UEs. This prevents the usability of the scheme in networks with irregular cell shapes and large number of edge users.

Centralized schemes as in [9] are too heavy for implementations as all interference information has to be gathered at the central entity [5]. In [9, 10], equal static power allocation to edge-RBs is used to reduce the computations. However, allocating different power can achieve higher spectral efficiency by allocating different power levels to the same RB in different cells. In addition, lower ICI can be achieved by reducing power levels of dominating interferers. Moreover, power waste can be reduced by exploiting the tradeoffs between over and under RB power allocations.

III. SYSTEM MODEL

The LTE-Advanced OFDMA downlink transmission in a multi-cellular network with I cells is considered in this paper.

A. User Classification

An eNB is located at the centre of each cell and allocates downlink resources in the time and frequency domains to each of the U_i active users with $i \in \{1,2,\dots,I\}$. Users in each cell are divided into center and edge UEs using an adaptive *Bandwidth Proportionality* SINR threshold that guarantees that the number of users in each class is proportional to the percentage of RBs allocated to the user's class.

B. Throughput Calculation

The total bandwidth B is divided into J channels (each of 12 orthogonal subcarriers occupying a total of 180 kHz). Time is divided into slots (0.5ms each). Each RB represents a single channel for the duration of one time slot. One or more RBs can be allocated to a UE at a time. Each RB is assigned exclusively to one UE at any point of time within a given cell; neighboring cells may use the same RB at the same time.

Each cell utilizes all system channels and operates with total transmission power P_i^{total} . The signal carrying the payload is transmitted by only one eNB. Signals coming from other eNBs are considered as ICI. The signal to interference plus noise power ratio (SINR) of the u^{th} user allocated to the j^{th} channel in the i^{th} cell is given by:

$$\gamma_{u,i}^{j} = \frac{G_{u,i}^{j}\, P_{u,i}^{j}}{\sum_k^I G_{u,k}^{j}\, P_{u,k}^{j} + N_0}, k \neq i \qquad (1)$$

where, $G_{u,i}^{j}$ is the channel gain between the u^{th} user and the i^{th} eNB using the j^{th} channel. $P_{u,i}^{j}$ is the transmission power allocated to the j^{th} channel by the i^{th} eNB to serve the u^{th} user. N_0 is the additive white noise power. The achievable rate on the j^{th} RB for the u^{th} UE in the i^{th} cell is given by:

$$R_{u,i}^{j} = C\left(\gamma_{u,i}^{j}\right) \qquad (2)$$

where $C(\cdot)$ is the adaptive modulation and coding (AMC) function that maps the SINR to rate. The modulation schemes range from the robust low rate QPSK scheme to the high rate but more error prone 64-QAM scheme.

IV. THE PROPOSED SCHEME

Considering the various drawbacks discussed in section II, the following objectives and guidelines are considered for designing the proposed scheme:

- *Autonomous and fast adaptation:* Resource allocation should be performed only at the eNB level, with no central coordinator for rapid adaptation to the variation in the number of users and their channels and power needs.
- *Computationally efficient:* The algorithm should be independent of the number of users and cells, in order to be suitable for use in crowded cells and large networks.
- *RB Power manipulation:* The algorithm should be able to assign different power levels to efficiently reuse the same frequency spectrum at spatially separated locations. Also, it should allocate more power rather than more RBs to edge-UEs to increase their rates.

A. Data Exchange Strategy

Achieving fast adaptation to the varying channel conditions requires minimizing the data exchange between eNBs. We adapt a modified version of the data exchange strategy presented in [10]. Similar to [10] each eNB sends only its calculated weights, instead of all of channel information of its users, to the neighboring cells on regular intervals. In our strategy, the weight of a cell with respect to a neighboring cell represents the *number of all users* in the cell (not only edge users as presented in [10]) for which the power of the signal received from the serving cell is less than the power of the signal received from the neighboring cell. By taking the center users into consideration when computing the weight in our strategy, the proposed scheme can adapt to highly moving users and prevents assigning very high power to edge users in one cell that can affect a center user in some neighboring cell.

The weight $w_{i,k}$ denotes cell i weight with respect to neighboring cell k as calculated at cell i using:

$$w_{i,k} = \sum_{u}^{U_i} H\left(P_{u,k} - P_{u,i}\right) \qquad (3)$$

where U_i is the set of UEs in the i^{th} cell. $H(x)$ is a unit step function, H(x) = 1 only if x > 0. Otherwise, $H(x) = 0$. $P_{u,k}$ is the received power by the u^{th} user from the k^{th} neighboring cell and $P_{u,i}$ is the received power by the u^{th} user from the i^{th} cell.

Smaller weights indicate that the serving cell would be least affected by interference from the other cell. Thus, each eNB periodically exchanges the weights it calculated with its neighbors over the X2 interface. Average weight is calculated to reflect both the effect of the serving cell interference on the neighbor's UEs and the effect of the neighboring cell interference on the UEs of the serving cell. $\widetilde{w}_{i,k}$ represents the average weight between the i^{th} and k^{th} cells, and is given by

$$\widetilde{w}_{i,k} = \frac{w_{i,k} + w_{k,i}}{2} \qquad (4)$$

Weight update messages are transmitted every 10 ms with no retransmission policy on drop. Every update message is time-stamped, thus, eNBs use the update message with the latest time-stamp to calculate the average weights.

Smaller average weights indicate that the serving cell would be least affected by interference from the other cell, and that the other cell as well will be least affected by interference from the serving cell. Thus, the serving cell can allocate more common channels to this neighbor. Repeating this process across all neighboring cells enables the allocation of minimum common frequency bands to cell-edge UEs.

On frame bases (every 10ms), each eNB solves the UE/Power-to-channel assignment problem individually using the information collected from its UEs and neighboring eNBs. The objective function carried out by the i^{th} eNB is minimizing the use of the same channels by edge users in neighboring cells:

$$f(i) = \min \sum_{j}^{J} \sum_{k}^{I} \widetilde{w}_{i,k}\; X_{i,j}\, X_{k,j} \quad ,k \neq i \qquad (5)$$

In all cells, the UE/Power-to-channel assignment employed at any given time should always result in having the sum of the number of channels allocated to users less than or equal the total number of channels available $|J_i|$:

$$\textstyle\sum_{u \in U_i} |J_u| \leq |J_i| \quad \forall i \in \{1,2,\dots,I\} \qquad (6)$$

The total power used in all channels must be less than or equal the maximum available eNB transmission power P_i^{total}:

$$\sum_{u\in U_i}\sum_{j\in J_u} P_{u,i}^{j} \leq P_i^{total} \quad \forall i \in \{1,2,..,I\} \qquad (7)$$

Each eNB tries also to minimize the number of unsatisfied UEs given by the Soft Constraint:

$$\sum_{j\in J_u} X_{i,j}\, R_{u,i}^{j} \geq R_u^{req}\ \forall\, u \in \{1,2,..,U\} \qquad (8)$$

where J_u is the set of channels allocated to the u^{th} user. R_u^{req} is the required rate of the u^{th} user. $X_{i,j}$= {0,1} represents the usage of the j^{th} channel in the i^{th} cell. $X_{i,j}$= 1 only if the j^{th} channel is being used in the i^{th} cell.

B. Harmony Search Mapping

Harmony Search (HS) algorithm is utilized to rapidly calculate the optimized UE/Power allocation updates by solving Eq. (5). The traditional HS proposed in [6] was extended to optimize two decision variables, namely, (1) UE to be allocated to each RB, and (2) power to be allocated to each RB. In the proposed scheme, each *instrument* corresponds to a *RB*. The list of *cords* of an instrument corresponds to the *UEs* in the cell. The range of *pitches* of a cord corresponds to the *power levels* (See Section IV.C). A *Harmony* between all instruments corresponds to *the UE/Power to RB assignment matrix*. Finally, *audience's aesthetics* correspond to the *matrix cost* based on Eq. (5).

The HS algorithm is initialized by creating a *Harmony Memory (HM)* of size *HM Size (HMS)*. The initial *HM* consists of a number of random Harmonies (possible solutions). After the *HM* initialization, the algorithm iterates until it reaches the *Maximum Improvisation (MI)* limit. At each iteration, the algorithm introduces a single new Harmony that replaces the worst Harmony in the *HM.* For each instrument (RB) in the new Harmony, the new chord (UE) and pitch (power level) can be selected from the *HM* with a probability of *HM Consideration Rate (HMCR).* Otherwise; they are generated randomly from the range of valid chords and pitches with a probability of *1-HMCR*. If the new chord and pitch were selected from the *HM*, then there is a probability of *Pitch Adjustment Rate (PAR)* to adjust the pitch (power). At the final iteration, the best Harmony (assignment matrix) is chosen.

C. Power Control Strategy

The proposed power control strategy is carried out by attempting to allocate more power to a UE that has not yet reached its required rate. The increments start by attempting to allocate 1.25X of the default power ($\frac{P_i^{total}}{|J_i|}$), and keep incrementing by a step of 0.25 until either the throughput of the UE increases or the power value of 3X is reached. To reduce ICI, the scheme attempts to minimize the allocated power to an UE that has satisfied its required rate without causing it to become unsatisfied. The scheme attempts to allocate 0.5X of the default power then keeps incrementing by a step of 0.1 until the UE becomes satisfied again.

D. Channel Restriction Strategy

To maximize the system throughput, each cell altruistically restricts channels based on the newly proposed *Selfishness Index (SI)* parameter, where $1 \leq SI \leq 20$. The higher the value of the index, the more the scheme becomes selfish and prefers allocating channels to its users rather than restricting them to enhance the quality of the channel in the neighboring cells. The strategy states that a channel is restricted if $\frac{RB\ achievable\ rate}{UE\ required\ rate} > SI$ or $\frac{RB\ achievable\ rate}{UE\ required\ rate} < \frac{1}{SI}$. The upper bound guarantees that the high achieving channels are allocated to UEs with high rate requirements to prevent the waste of "good" channels. The lower bound, on the other hand, guarantees that UEs are allocated their highest achieving channels to minimize the number of channels per UE in order to allow for allocating those channels to other UEs that can achieve better rates, or preventing their usage to minimize ICI.

E. Algorithm Computational Complexity

The computational complexity of the proposed algorithm is a function of the *constant MI* iterations on the *HM* used to generate new Harmonies. Each new Harmony requires iterating on all *J* instruments (Channels), assigning chords (UEs) randomly, thus, is *independent of number of UE*, and sets the pitches (Power) according to the power control strategy. The cost of each of the *MI* iterations is *O(J).* Thus, the overall complexity is *O(MI × J)*, and hence, it is independent of the number of users, cells, and power levels.

V. Simulation Results and Analysis

A. Simulation Setup

Simulations were performed using the WINNER - Phase II (WIM2) shadowing and fading models [11] to generate a radio channel realization for a metropolitan suburban environment. Initially, UEs are randomly dropped and configured to dynamically move with random speeds between 0 m/s (stationary) and 100 m/s (on a speedy train) in random directions (for a certain UE, the speed and direction are constant throughout the simulation). Three hexagonal cell layout of 500 m radius each was considered, wherein each cell is equipped with an eNB with an omnidirectional antenna located at the cell centre. The bandwidth *B* is 20 MHz and the number of channels $|J_i|$ is 100. Total transmission power in each cell P_i^{total} is 40W, and the additive white noise power N_0 is -114dBm/Hz. Full buffer traffic model was considered for all users as it represents the worst case from the ICIC performance assessment perspective. Handover was executed at 3dB. Statistics are collected in the 3 cells over the time duration of 1000 frames. For HS, the values of the *HMS*, *MI*, *HMCR* and *PAR* were set to 200, 200, 0.5 and 0.5, respectively.

Proposed scheme performance is compared to four reference schemes, *Reuse-1*, *Reuse-3*, *PFR* and *SFR,* along with the *Kimura* scheme [10]. Proportional Fairness (PF) Scheduling is used by other schemes while the proposed scheme uses *HS.*

B. Performance Analysis

Fig. 1 depicts the Cumulative Distribution Function (CDF) of the Time-Average UE Throughput (TATP) under high mobility. In case of Reuse-3, with no ICI and PF Scheduling, all UEs have similar TATP (steep slope in Fig. 1). However, Reuse-3 achieves the worst TATP since all UEs share a small portion of the Bandwidth. Both Kimura and SFR schemes achieve higher edge TATP than PFR scheme due to the availability of more RBs to edge UEs. Kimura achieves edge TATP less than SFR due to allocating a number of RBs with high power to more than one neighboring cells. Both Reuse-1 and SFR schemes achieve the same edge TATP. SFR has a limited number of edge RBs, but uses higher power, while Reuse-1 has more RBs for edge UEs but uses less power.

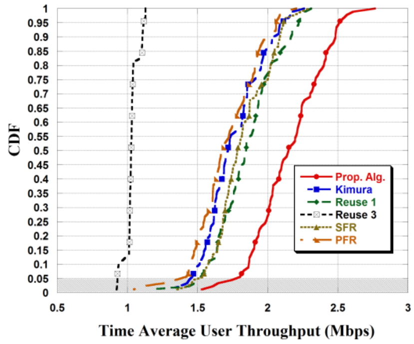


Figure 1. CDF of TATP for 30 users/cell at 3Mbps/user. The 5% throughput (highlighted) presents edge TATP.

Similar to Reuse-1, the proposed scheme does not dedicate any portion of the allocable bandwidth to any user class, thus edge RBs are *dynamically* redefined every frame. However, unlike Reuse-1 and similar to Kimura, both the information fed back from the cell UEs and the weights exchanged between eNBs are used to minimize ICI. This in turn leads to a higher edge TATP for the proposed scheme compared to all other schemes. Similar to Reuse-3 and PFR, the new scheme restricts channels in some cells to further minimize the ICI. However, it does the restrictions *dynamically* based on the *SI*, which prevents stalling due to the unavailability of channels. Similar to SFR and PFR, the proposed scheme uses different power levels. However, power levels are determined *dynamically* for each RB-UE allocation with the objective of increasing the SINR for unsatisfied users and decreasing the power consumption for satisfied users. The proposed scheme achieves a slightly lower fairness (less steep slope of the curve in Fig.1). This is expected as, unlike the PF scheduling used by other schemes, the proposed algorithm attempts to satisfy the largest amount of users as formulated in the constrain given in Eq. (8).

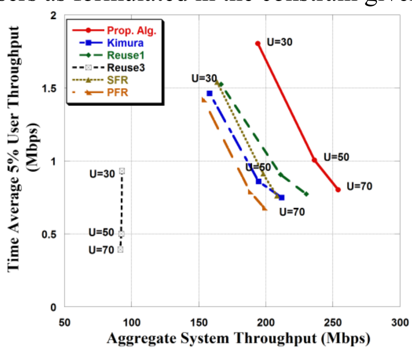


Figure 2. Edge TATP Vs ATP for (30,50,70) users/cell with 3Mbps/user.

Fig. 2 presents a closer look at the performance of the schemes under different number of UEs. As expected, the general trend is that as number of UEs *U* increases so does the Aggregated system Throughput (ATP). On the other hand, the edge TATP decreases because more UEs share the same resources. For the same number of UEs, the proposed scheme always achieves higher edge TATP and system ATP. It is worth noting that at a smaller number of users (e.g., 10 users per cell), Reuse-3 achieves the highest edge TATP as expected followed by the proposed scheme, while Reuse-1 has the worst value due to the excessive ICI. These results; however, are omitted from Fig.2 for clarity. It can be deduced from comparing the performance at small and large number of UEs that, ICI effect on the edge TATP is only significant when there are enough resources to serve all UEs; otherwise allocable resources size has higher significance.

Fig. 3 presents the power efficiency, which is calculated by dividing the system throughput by the power consumed. The general trend for all schemes is that, as number of users *U* increases, so does the power efficiency. This is due to the increase in the system ATP. However, as all RBs in Reuse-3 consume the same amount of power and achieve the same rate, since there are no ICI, the system ATP and power efficiency remain constant with the different number of UEs. Reuse-3 achieves low power efficiency because of the limited allocable bandwidth, which limits the maximum achievable rate. As can be expected, Reuse-1 and SFR achieve higher power efficiency than that of Kimura scheme, as they can achieve higher system ATP. Interestingly, PFR also achieves higher power efficiency than Kimura scheme while it has always achieved lower system ATP. Our analysis of the Kimura scheme shows that, on average, 25% of the edge RBs are used by more than one cell with equal high power resulting in high ICI, and hence, the Kimura algorithm allocates more RBs to UEs to satisfy their required rate leading to power consumption larger than that of PFR which has isolated edge RBs.

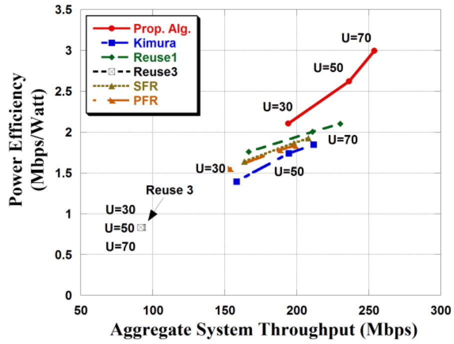


Figure 3. Power efficiency Vs ATP for (30,50,70) users/cell with 3Mbps/user.

As shown in Fig. 3, for the same number of UEs, the proposed scheme has significant higher power efficiency and system ATP than all other schemes for all *U* because of the power control and channel restriction strategies. With power control, the proposed scheme allows some RBs to be allocated to edge UEs in two or more neighboring cells, but with *different power levels,* unlike Kimura scheme, thus achieving an acceptable SINR for the UEs and lower power consumption. The channel restriction strategy prevents power wasting by not allocating RBs that suffer from high ICI. This approach conserves power in the restricting cell while increases the RB throughput in neighboring cells. The proposed scheme curve in Fig. 3 has a steeper slope as compared to other schemes indicating that as the number of UEs increases, only small extra power is consumed. The proposed scheme only allocates extra RBs if this would lead to a significant throughput increase. Thus, with less RBs used, less power consumed.

C. Sensitivity Analysis

A one frame to five frames delays of the weight update messages analysis shows that the TATP does not degrade if the delay of the X2 interface is lower than 5 frames (50ms). It is therefore shown that, the proposed method is sufficiently robust for the weights update messages delays as the next generation mobile networks backhaul must guarantee end-to-end maximum two-way delay of 10ms [12].

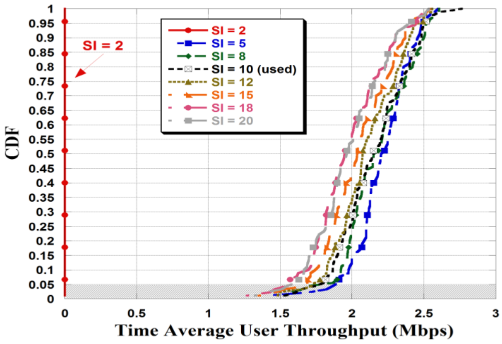
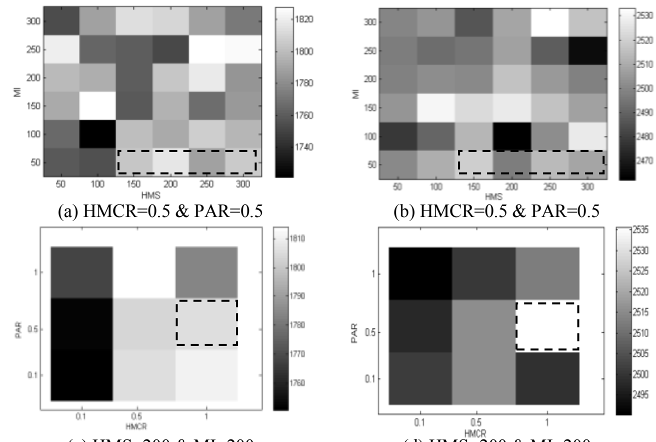


Figure 4. Effect of the *SI* on TATP for 30 users/cell at 3Mbps/user.

In Fig. 4, the effect of the *SI* is evaluated. At low SI (e.g., *SI=2*), a channel must be able to achieve 0.5 of the UE required rate to be allocated by the proposed algorithm. Thus, at *SI=2*, all eNBs restrict all channels as they see that all channels will not achieve a significant rate if allocated to any UE leading to a zero throughput. The best TATP is achieved with *SI* values between 5 and 10 as there is a large number of RBs allocated by the eNB but not large enough to cause significant ICI. With *SI* values above 10, each eNB becomes very selfish and prefers to allocate RBs to its UE rather than leaving them to neighboring eNBs, which results in an increase in ICI, and thus, a decrease in the TATP.



(a) HMCR=0.5 & PAR=0.5 (b) HMCR=0.5 & PAR=0.5

(c) HMS=200 & MI=200 (d) HMS=200 & MI=200

Figure 5. Effect of *HS* parameters on 5% UE throughput (left) and 95% UE throughput (right) for 30 users/cell at 3Mbps/user.

As shown in Fig. 5, the performance of the proposed scheme is slightly affected by the various HS algorithm paramenters (*HMS, MI, HMCR,* and *PAR*). However, as the computation complexity of the proposed scheme is dependent on the *MI*, small *MI* values are recommended, such as: *MI=50* and *HMS≥200* (dotted rectangle in Fig.5-a and 5-b). The analysis of the *HMCR* and *PAR* results shows that their best values are, respectively, *1.0* and *0.5* (dotted square in Fig.5-c and 5-d). It can be concluded from this analysis that having an initial large *HM* allows fast convergance to a good solution.

VI. Conclusion

In this paper, we proposed a novel decentralized dynamic ICIC scheme based on Harmony Search (HS) algorithm for highly mobile users in multi-cell LTE-Advanced systems. The proposed scheme does not require any central coordination or frequency planning and the inter-cell message exchange is minimized. Thus, the scheme can be deployed in the LTE-Advanced flat network architecture and is robust to the X2 interference delay and high user mobility. Unlike existing dynamic ICIC schemes, computations are independent of the number of users and cells in the system, making it more practical for deployment in large networks with rapidly moving users. Scheme's performance is slightly affected by the values of the *HS* parameters. The proposed power control and channel restriction strategies were proven to reduce the power consumption and ensure a better edge throughput without impacting the overall cell throughput.

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