On the Performance of Static Inter-cell Interference Coordination in Realistic Cellular Layouts*

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Abstract. Effective interference management has been recognized by the industry and standardization bodies as a key enabler for 4G systems. This work is about static Inter-Cell Interference Coordination for OFDMA based cellular networks such as LTE. The majority of previous ICIC studies, both theoretical and simulation-based, have been conducted considering synthetic and/or small cellular layouts. In this work, the performance of static ICIC strategies in non-regular cellular layout is studied introducing some related RRM functions in the methodology. The overall performance assessment gives special attention to the efficiency vs. fairness tradeoff and the elements associated to it. Results show that the design of suitable and effective ICIC schemes for realistic cellular networks can not be done by simply extending classical approaches.

Keywords: Long Term Evolution, Inter-cell Interference Coordination, Radio Resource Management, Soft and Fractional frequency reuse.

1 Introduction

The International Telecommunications Union - Radiocommunication Sector (ITU-R) has defined a set of features that must be fullfilled by the so called International Mobile Telecommunications-Advanced (IMT-A) systems. Broadly speaking, these systems must be able to support high-quality mobile multimedia applications and fullfill the evolving users' needs [1]. Consequently, mobile operators are optimizing and upgrading their networks according to the evolution of the most popular technologies: the Long Term Evolution (LTE) [2] and WiMAX [3]. In particular, LTE has been described as a 3.9G (beyond 3G but pre-4G) technology since its first release LTE does not meet IMT-advanced requirements for 4G. However, the 3rd Generation Partnership Project (3GPP) is currently developing LTE Advanced which is a preliminary mobile communication standard, formally submitted as a 4G system candidate to ITU as a major enhancement of the LTE standard [4,5,6]. The target of 3GPP LTE Advanced is to reach and surpass ITU requirements.

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LTE (and WiMAX) employs Orthogonal Frequency Division Multiple Access (OFDMA) as access technology for the downlink [7] mainly due to its flexibility for resource allocation and because OFDMA provides intrinsic orthogonality to the users within the cell, which translates into a almost null level of intra-cell interference. Therefore, inter-cell interference is the limiting factor when high reuse levels (to achieve higher spectral efficiency) are intended. On the other hand, the new requirements for IMT-A include delivering higher peak rates to support advanced services (up to 1 Gbps for low mobility) and enhanced and uniform levels of quality of service within the cell area [8]. Nevertheless, from the network perspective, this is not a trivial task since users far away from their serving access point, typically perceive a significant amount of inter cell interference. Then, as a direct consequence of this situation, the fairness among the Quality of Service of users is jeopardized.

Given this, initiatives and proposals have been formulated within the 3GPP to cope with inter-cell interference. In particular, three main strategies [9,10] are proposed : Inter-cell Interference (a) Coordination (ICIC) (b) randomization and (c) cancellation. Although, inter-cell interference randomization [11], and cancellation [12] have received some attention, ICIC has been the field in which more contributions are being done, and it has been idenfied as a key element by the industry [13,14], and the research community [15,16]. The so called *soft* and *fractional* frequency reuse schemes (SFR and FFR respectively), have been widely studied. Reference works are: [17,18,19,20,21]. Although, the scope and manner in which the authors address the subject is varied, there are some similarities. Most of the existing literature addresses the ICIC issue by means of synthetic (and very often small) cellular layouts. The extention of these results to realistics scenarios is questionable mainly due to two reasons: the inter-cell interference is not uniform, this means that not all the cells receive the same amount of interference, as it does happen in a perfectly geometric layout. Second, when the effects of inter-cell interference are studied, the scenario must be large enough to asure that a at least 3 or more interferer tiers are considered. The latter is especially important in OFDMA networks taking into account that the wireless channel is frequency selective.

To the best of the authors knowledge, only very recent works [22] have addressed ICIC by considering large scale/realistic scenarios. In this work, the authors claim that for real networks with an irregular coverage pattern, no simple reuse scheme can be applied in a straighforward way. In this excelent contribution, the authors estimate the average throughput map over the entire service area by considering only large scale fadings effects. This approach allows a cell edge performance assessment without significant complexity involved.

In this paper, we do consider a large scale/realistic network as in [22] but with some important differences. First, from the system model perspective, we have evaluated the ICIC gain considering the constrains associated to the frequency domain scheduling (proportional fair discipline is considered) and the effect of the Adaptive Modulation and Coding (AMC). We strongly agree with the authors in [23] in that *the impact of ICIC on the overall system throughput* must be analyzed through a model in which the interactions with additional Radio Resource Management (RRM) functions, such as scheduling, adaptive modulation and coding and power control are captured. With this, the analysis is more precise in the sense that also takes the frequency selectiveness of the channel into account. Second, from the performance evaluation point of view, not only system oriented metrics are considered, but also user oriented ones. This is important since improving fairness while keeping spectrum efficiency as high as possible is the main target of ICIC strategies.

In this manner, the contribution of this paper is a comparative analysis of several static ICIC strategies in a very realistic test bench in which the cross effects between ICIC and the additional RRM functions are weighed up. Results not only quantify ICIC gains by means of a comprehensive set of performance metrics but also provide hints about where to go in future studies.

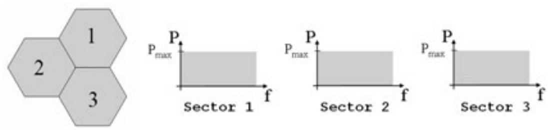
The paper is organized as follows, Section 2 introduces the ICIC schemes considered. Next, Section 3 includes the description of the simulation scenarios, the system model, the performance metrics and the particular configuration we have used for each scheme. The analysis of results, taken into account existing/related results from previous contributions, is presented in Section 4. Finally, conclusions and additional remarks close the paper in Section 5.

2 Description of Static ICIC Strategies

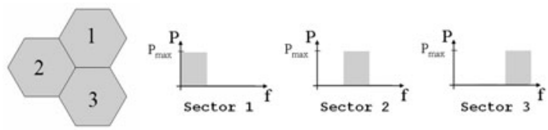
In this section, we present a detailed description of the static ICIC strategies considered for this study. In particular, 4 different schemes with different values of frequency reuse (FR) have been selected. The two first schemes, the so called full frequency reuse (FR=1) and fixed reuse 3 (FR=3), were selected as they represent the benchmark in terms of spectral efficiency and fairness respectively. Thus, a more coherent performance assessment of the two properly said ICIC strategies, *Soft Frequency Reuse* (SFR) and *Fractional Frequency Reuse* (FFR) can be done. These two strategies have been shown [24,25] to be intermediate points between FR=1 and FR=3. In addition, these strategies have been widely studied as ICIC schemes in the vast majority of contributions based on synthetic/theoretical scenarios. Therefore, the selection of these strategies is the natural choice according to our target. A generic representation of the selected static ICIC schemes is shown in Fig. 1.

In static ICIC schemes, the resources (bandwidth and power) allocated to each cell do not change over time. Then, each cell uses those resources autonomously and according to the rest of RRM functions. Nevertheless, depending on such *resource-to-cell allocation*, more or less freedom is left to finally pair the resources to the users.

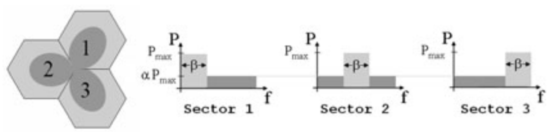
ICIC S1: Static ICIC scheme S1 is also known as full frequency reuse, since reuse factor 1 is aplied to the whole network. In this case, there is not constraint at all on the usage of resources within each cell. This scheme is attractive since it has been shown in [15] that it provides the best overall spectral efficiency.



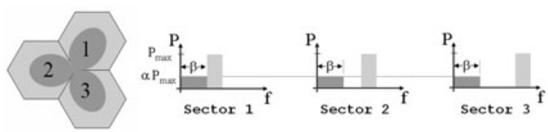
(a) ICIC S1.



(b) ICIC S2.



(c) ICIC S3.



(d) ICIC S4.

Fig. 1. Generic power profiles in static ICIC schemes

Nevertheless, users close to the cell edge experience a significant amount of inter-cell interference.

ICIC S2: Employing reuse factor 3 is the traditional choise followed by network operators in tri-sectorial deployments. In this case, the levels of inter-cell interference experienced by cell edge users are significantly reduced at expense of the overall network efficiency. Similarly to the previous case, cells employ their resources without restrictions.

ICIC S3: This strategy corresponds to soft frequency reuse. This approach can be considered as an intermediate point between the two previous strategies in the sense that reuse factor 3 is applied to the cell edge users while central users do more aggressive usage of the spectrum. Soft frequency reuse implies the need to classify users within each cell. The criterion is often based on the average channel quality [26], [27]. Two possible approaches can be taken into account:

1. *Class Proportionality*: SINR thresholds are selected so that each class has the same average number of users.
2. *Bandwidth Proportionality*: The threshold guarantees that the number of users is proportional to its allocated bandwidth.

Table 1. Simulation scenarios details

Scenario	Cells	Area [Km^2]	Density [Cells/Km^2]	SINR$_{TH}$ [dB]
A	171	33.2	5.15	1.85
B	42	32.9	1.28	2.50

In this study, only class proportionality is considered. The reason is twofold. First, study the impact of the classification thresholds on ICIC performance is out of the scope of this work, hence keep fixed this degree of fredom is a necessary condition to get valid results. Second, the particular choice of class proportionality is due to the fact that it is an approach commonly employed in previous contributions [28,26] dealing with static ICIC, thereby facilitating comparisson and analysis.

It is worth to note that while central users receive inter-cell interference of type *inter-class* (coming from users of different class) and *intra-class* (coming for users of the same class), cell edge ones only receive inter-class interference. Finally, the amount of interference received by the cell edge users and the their bandwidth size are controlled by the parameters α and β respectively.

ICIC S4: As in ICIC S3, two different classes are considered, nevertheless the main difference in this case is that the inter-class interference is completely removed, i.e. each class has exclusive use of its bandwidth. This is important because the performance in terms of throughput and fairness becomes independent of α since the SINR does not depend on the transmitted power (equal for all cells) as long as the inter-cell interference level is significantly higher than the noise floor. The parameter β controls the width of the band allocated to central users, hence it also determines the bandwidth available for outer ones.

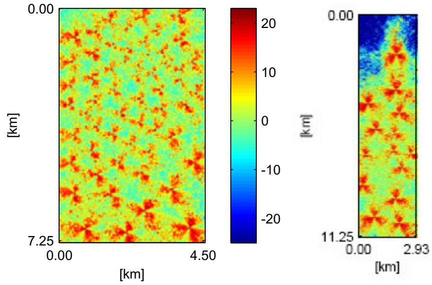
3 Experiments Description

In this section, a complete description of the experiments is provided. The different sub-sections explain the overall methodology.

3.1 Simulation Scenario

The simulated scenario is a realistic one covering the city of Vienna and its surroundings. The digital elevation model, system layout and propagation data has been obtained from the MORANS initiative [29]. This activity was framed within the European COST 273 Action and aimed at providing common system simulation environments so that different researchers can compare results.

In particular, two sub-areas having different cell densities were selected for comparisson purposes. Figure 2 depics the resulting average SINR map for both zones. Additional details are shown in Table 1.



(a) Scenario A (b) Scenario B

Fig. 2. Realistic simulation scenarios

3.2 System Model and Methodology

Additionally to the cellular layouts described previously, the cells' downlink configuration follow the setting established by the LTE standard [7,30,31]. Both the simulation scenario and the LTE's OFDMA setting complete the system model in which users are randomly allocated. For each scenario, an average density of 50 users per cell was considered. The traffic model considered for all users is full buffer. The choice of this model, from the ICIC performance assessment perspective, can be considered as a worst case since it assures that each cell will transmit power over its whole available bandwidth leading then to the worst situation in terms of inter-cell interference. The implementation was done by means of an OFDMA system level simulation platform that has been developed in C++. The link-to-system level interface largely follows the guidelines given by [32].

Specifically, the system has 100 physical resource blocks (PRB) available for the users (18 MHz, 1200 sub-carriers of 15 kHz). Note that a Physical Resource Block (PRB) is the minimum bandwidth the scheduler can assign to one single user. Transmission time intervals of 1 ms containing 10 OFDMA symbols are considered. The total available power at each cell is 43 dBm and sum power condition is always kept. ITU Extended Typical Urban (ETU) have been considered as channel model. 8 dB log-normal shadowing is applied following the model proposed in [33] with a correlation coefficient between cells equal to 0.5. It is important to stress that achievable rates were computed taking into account the instantaneous channel conditions (including the frequency selectiveness of the channel) and according to the adaptive modulation and coding used in LTE, as specified in [34]. This mapping has been done using the link abstraction model based in mutual information at modulation symbol level [35], which outperforms the classic Effective Exponential SINR model because it is able to predict the BLER with higher accuracy, particularly for higher order modulations, such as 64-QAM. Additionaly, Proportional Fair Scheduling is autonomously executed at each cell to make the final pairing of resources to users according to the following expression:

$$m^*(t,n) = \underset{m}{\operatorname{argmax}} \frac{T_{m,n}(t)}{\sum_{k=0}^{t-1}\sum_n T_{m,n}(k)} \quad \forall n \in N_L \tag{1}$$

where $T_{m,n}(t)$ is the achievable throughput if the PRB n is assigned to the user m at time t. N_L is the set of PRBs available at cell L.

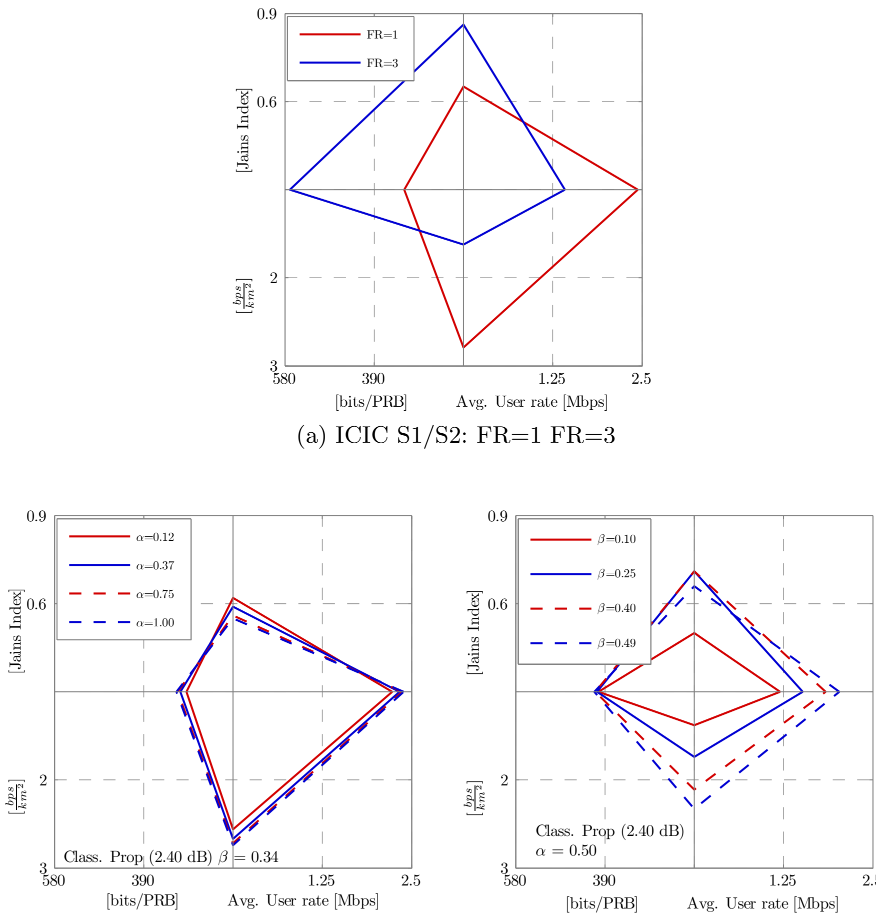
To conclude this section, the description of the experiments is provided. As stated earlier, two different scenarios (see Table 1) and 4 different static ICIC strategies (see Fig. 1) were considered. Specifically for ICIC schemes S3 and S4, the impact of the parameters α and β on the overall performance was also studied. In particular, for SFR, a linear variation of α (0.2 0.4 0.6 0.8) was considered while two values of β (0.16 0.33) were also taken into account. Note that for the tri-sectorial arrangement, β must be smaller than 0.33 when SFR (as in 1c) is applied. For FFR, the values of α were kept as in SFR but an additional value of β (0.67) was considered. The choice of these particular values is to keep consistency with previous contributions in which similar variations of these parameters was considered to assess the performance of static ICIC strategies in synthetic scenarios and so, obtain reasonable conclusions based on our results.

3.3 Performance Metrics

As it was commented previously, the analysis is mainly focused on the efficiency vs. fairness tradeoff. Neverthelss, additional metrics were also considered to better understand the whole network behaviour. In particular, the set of metrics includes: a fairness measure, the Jain's index [36], the system spectral efficiency per area unit ($\frac{bps}{Hz \cdot km^2}$), the average user rate (Mbps) and the average number of bits per PRB ($\frac{bits}{PRB}$) to take into account the effectiveness in the resources usage. All these metrics were computed based on Monte Carlo simulations.

4 Analysis of Numerical Results

In this section, the results obtained for the experiments previously described are presented. It is important to recall that the main target of this study is to assess the performance of static ICIC strategies in realistic scenarios and compare them with the ones already reported for synthetic cellular layouts. To do this, we will take as reference results and conclusions from some previous contributions considering synthetic scenarios [28,37,17]. In particular, results taken from [28] are illustrated in Fig 3 as main reference. By comparing Fig 3a with Figs 3b and 3c, it is clear that schemes S1 and S2 are the benchmarks in terms of spectral efficiency and fairness respectively. This is a well known result in the context of static ICIC in synthetic cellular layouts. On the other hand, the results corresponding to this work (for realistic cellular layouts) are presented in Figs 4, 5 and 6. These figures correspond to the cases of FR=1/FR=3, SFR and FFR (for both scenario A and B) respectively.



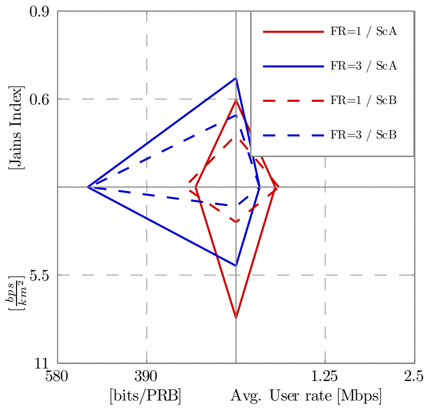
(a) ICIC S1/S2: FR=1 FR=3

(b) ICIC S3/S4: SFR

(c) ICIC S3/S4: FFR

Fig. 3. Reference results from synthetic scenarios

Looking at Fig 4, the well known rule of thumb [27] that states that S1 offers the highest spectral efficiency with poor fairness, while S2 boosts the opposite also applies in realistic networks. The main difference appears when quantifying this losses/gains. Thus, for example the throughput gain in scenario B is clearly smaller than in A or synthetic scenarios. On the other hand, the fairness gain is proportionally smaller in the scenario A than in sceneario B. Comparing the results of S1 and S2 in synthetic and realistic scenarios (beyond the absolute magnitudes), the impact of such schemes on the performance metrics is clearly different for the different scenarios, especially for the case of fairness and average users rate although the overall behaviour still holds in realistic networks in the sense that S1 favorates the efficiency while S3 favorates the fairness.



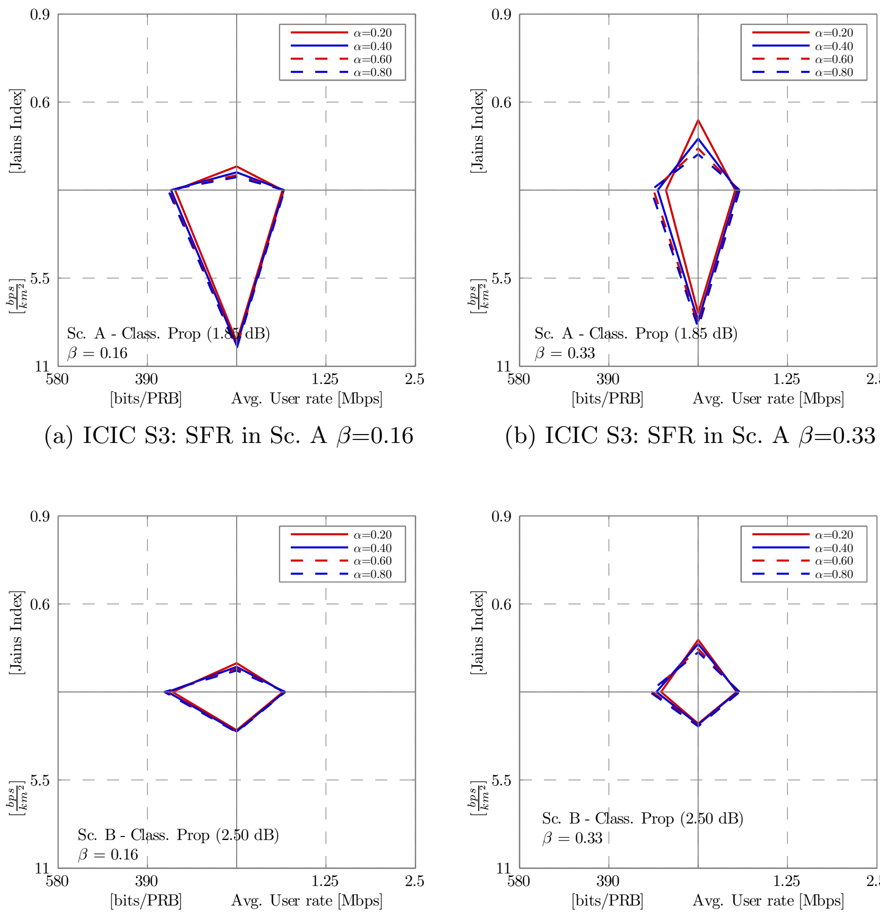
(a) ICIC S1/S2: FR=1 FR=3

Fig. 4. S1/S2: FR=1 FR=3 Sc. A/B

Figure 5 depicts the results corresonding to SFR in which different values of α were evaluated for two different values of β for both scenario A and B. Again, what we can see, by considering the case of β=0.34 is that the impact of the parameter α on the different metrics is different in realistic scenarios compared with the result shown in Fig 3b for synthetic cellular layouts. Nevertheless, the overall behaviour for SFR is, in general terms, similar to the one observed in synthetic scenarios: (a) the greater the value of α the greater the spectral efficiency and (b) the lower the value of α the greater the value of fairness. However, one common aspect to both realistic scenarios is that a greater value of β favorates the sensitivity of the metrics to the values of α and so an easier tunning can be achieved. This is expected as β controls the portion of bandwidth allocated to the exterior users.

In Fig 6, the perfoemance of S4 is shown for both scenario A and B. Note that in both cases only one value of α is considered (0.20). The reason is that, similarly to synthetic scenarios, in fractional frequency reuse schemes, the overall performance becomes independent of α. Thus, results shows an interesting situation. In both scenario A and B the value of β is proportional to the spectral efficiency, but the fairness shows a maximum point for a intermediate point of β (different for each scenario). Also, we can note that the sensitivity of the performance metrics to the value of β is quite different in realistic networks due to the irregular geometry. All this behaviour is expected since β has to do with the bandwidth sharing between classes, and the definition of such classes implies setting up the SINR thresholds which in turn depends strongly on the layout under consideration. So, it follows that the choice of an optimal value for β depends on the network under consideration.

From the previous observations, it is clear that the optimal setting in terms of ICIC is particular to each geometry and that the best performance can not be

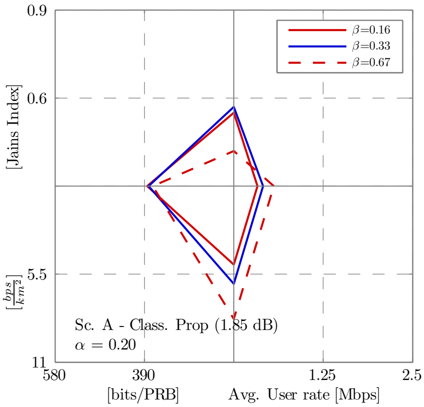


(a) ICIC S3: SFR in Sc. A β=0.16 (b) ICIC S3: SFR in Sc. A β=0.33

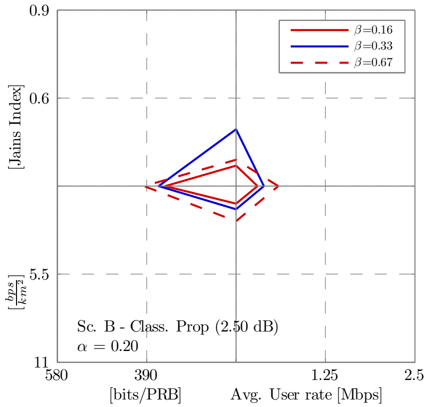
(c) ICIC S3: SFR in Sc. B β=0.16 (d) ICIC S3: SFR in Sc. B β=0.33

Fig. 5. S3: SFR in scenarios A and B

obtained by simply applying the traditional/homogeneous ICIC schemes (based on identical power mask for each cell). Even in situations in which the overall system performance seems to be good, an static/homogeneous ICIC pattern could penalize cells receiving more interference due to the irregular layout. Thus, although there are some important similarities between the results observed in synthetic scenarios with respect to realistic ones, there are also important differences. The first one, from the whole system performance perspective is that the optimum tunning is clearly network dependent and the second one, from the individual cells perspective, is that irregular cellular layouts leads inevitably to non-regular bandwidth allocations.



(a) ICIC S3: FFR in Sc. A α=0.20



(b) ICIC S3: FFR in Sc. B α=0.20

Fig. 6. S3: FFR in scenarios A and B

5 Conclusions and Future Work

A fair comparisson among different static ICIC strategies has been presented in this work. The results were obtained by running simulations over realistic cellular layouts and by considering additional RRM functions. The overall study was focused on the assessment of the performance of static ICIC strategies.

The main conclussions are summarized as follows:

- Classical ICIC strategies cannot be applied in a straighforward manner to non-regular cellular layouts claiming at their optimality at the same time. The performance of such strategies is different from one network to another. Tuning the network in realistic deployments must take into account several factors such as changing network load, traffic and mobility patterns, the local geometry and the associated/available network functions.
- The study of ICIC on non-regular cellular layouts open a promizing research line as it raises interesting open problems. A sufficiently generic framework that can be extended to realistic deployments has not been formulated. The relationship between ICIC and other RRM functions in the context of non-regular layouts has not been modeled neither. Because of this, the study of ICIC should not be addressed without the knowledge of the whole network picture.
- At this point, logical extensions to this work have been identified: (a) How to further exploit the connections between ICIC and additional RRM functions and network-dependent features appear as a natural direction to follow and (b) time varying network conditions could serve as a basis for designing of more flexible (but simpler) ICIC schemes. These schemes must be supported

by the limited amount of ICIC-oriented mechanisms available in the standards. In this sense, results clearly point towards the design of semi-static and dynamic ICIC schemes.

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