RIA-ICCS: Intercell Coordinated Scheduling Exploiting Application Reservation Information

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***Abstract*—Intercell coordination and cooperation techniques are some of the most promising approaches to increase the spectral efficiency of future wireless systems as required by the forecasted market needs. Among them, intercell coordinated scheduling (ICCS) arises as a near-term feasible solution due to its lower inter-BS communication requirements when compared to full cooperative approaches. In this paper we present our proposed Reservation Information Aware Intercell Coordinated Scheduling (RIA-ICCS) solution which considers application reservation information when constructing an interference graph for ICCS purposes.**

Our results shows that i) RIA-ICCS allows to significantly reduce the number of edges in an interference graph for ICCS solutions and its benefit increases as the number of mobile stations grows, i.e., when the system needs it most and ii) the reduced number of edges in the interference graph can be effectively translated to a lower blocking probability using state-of-the-art resource allocation algorithms.

***Index Terms*—IMT-A, 3GPP LTE, LTE-A, 3G, 4G, IEEE 802.16, IEEE 802.16m, Intercell Coordination, Interference Graph, Scheduling.**

I. Introduction

Wireless networks are a key element of today's society to communicate, access and share information. The wide range of uses that people make of wireless networks capabilities plus the forecasted exponential capacity growth needs (mainly due to video services) continuosly push research efforts towards achieving higher spectral efficiencies.

Fourth-generation (4G) broadband wireless technologies such as 3GPP LTE-A [1] and IEEE 802.16m [2] are the main solutions addressing the predicted future capacity needs as defined by the ITU IMT-A requirements [3]. One of the fundamental paradigm changes considered by 4G technologies to achieve higher spectral efficiencies is to move towards full frequency reuse, as much as possible, by exploiting intercell coordination techniques. Such an approach though, requires of interference mitigation and/or cancellation techniques in order to outperform current frequency planning solutions.

Interference mitigation and/or cancellation techniques have been used for many years in the past and they basically exploited orthogonality of time, frequency and/or spatial resources. Lately, more advanced solutions have been designed which actively reduce or cancel interference when orthogonality can not be guaranteed. Mechanisms supporting inter-base station coordination and cooperation are included both in 3GPP LTE-A and IEEE 802.16m. [4], [5] and [6] provide an overview of the different coordination and cooperation possibilities considered including: interference-aware detection, joint multicell scheduling, interference prediction, multicell link adaptation, joint multicell signal processing, coordinated scheduling and coordinated beamforming.

Among the different technology enhancements exploiting inter-base station coordination, in this paper we focus in intercell coordinated scheduling (ICCS). ICCS consists in coordinating the frequency/time resources used among multiple base stations with the objective of maximizing the overall network throughput and minizimizing interference. It is considered a feasible inter-BS coordination method in the short-term because of its lower signaling capacity requirements as compared to more complex approaches.

The contribution presented in this paper consists in our proposed Reservation Information Aware Intercell Coordinated Scheduling (RIA-ICCS) solution which considers application reservation information when constructing an interference graph for ICCS purposes. The main novelty of the proposed RIA-ICCS approach is the modeling of the resource reservations such that an a priori abstraction of the scheduling process impact on the interference graph edges can be performed. This results in a reduced number of edges and thus, a higher radio resource utilization efficiency.

II. Related Work on Intercell Coordination

Intercell interference is a major limiting factor for fulfilling ITU's IMT-A requirements [3] in future wireless networks. The coordination between base stations (BSs) for intercell interference mitigation is a promising approach which is the focus of a major body of research specially related to 3GPP's coordinated multipoint (CoMP) transmission and reception techniques. Most of the existing work in CoMP focuses on closed-loop schemes which promise a significant increase of the cell-edge users' throughput. An overview of the different methods under consideration in the CoMP area can be found in [5] and [6].

Given that some CoMP approaches (e.g. joint processing) impose severe inter-BS communication requirements both in

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latency and capacity terms (not expected to be feasible in the mid-term) intercell coordinated scheduling (ICCS) arises as a promising solution to increase the spectral efficiency of future systems at an affordable inter-BS communication cost.

In [7] the capacity gain from ICCS was analyzed yielding gains in the range of 25% to 50% in dense, interference limited networks depending on the network topology. Further research in the area considering multi-antenna systems [8] found that the capacity gain over conventional frequency reuse is O(min(M_r,M_t)$\sqrt{logN_s}$) for time division where N_s is the number of cooperating base stations in an $M_t \times M_r$ MIMO system.

A practical approach for dynamic intercell coordinated interference avoidance is proposed and analyzed in [9]. The solution designed achieves equivalent or better cell-edge throughput than static and partial frequency reuse schemes at no sector throughput cost. Moreover, as the scheme does not require frequency planning, it can be applied not only to macro-cell scenarios but also to small cells and femto cells.

Finally, in [10] a coordinated scheduling, beamforming and power allocation scheme across multiple base stations was proposed. This approach showed significant throughput and network utility improvements with coordination only at the resource allocation level with no data signal exchange.

Our contribution in this paper complements the aforementioned related work by exploiting a source of information which has not been considered for intercell coordinated scheduling in the literature to the best of the authors' knowledge: resource reservation information. Based on this information a finer prediction of the intercell interference can be performed, resulting in system performance gains as we will show in the next sections.

III. Reservation Information Aware Intercell Coordinated Scheduling (RIA-ICCS)

In the previous section we have reviewed different intercell coordination and cooperation solutions already available in the literature. In this section we describe our proposed enhancement to intercell coordinated scheduling (ICCS) solutions based on considering application reservation information.

Our proposed Reservation Information Aware ICCS solution (RIA-ICCS) consists in three main steps. First, construction of a multi-base station interference graph. Second, application of our designed graph reduction algorithm based on available reservation information. Third, application of a time/frequency resource assignment algorithm considering the reduced interference graph. In the following these three operations are described in detail.

A. Interference Graph Construction

Graph-based interference coordination has been extensively studied in the literature and different solutions are available depending on the time-scale of operation desired (static, semi-static and fully-dynamic) as well as their degree of processing distribution (centralized, distributed and local schemes). See for instance [4] for a detailed description and relevant references. Based on the implementation choice, an interference graph is constructed indicating critical interference relations between network nodes such that the largest interferers are blocked from using simultaneously the same set of resources.

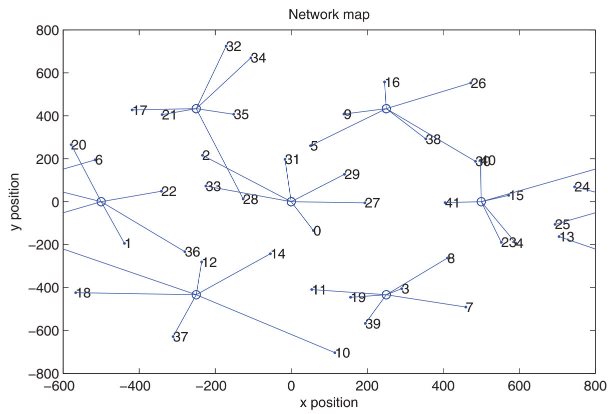


Fig. 1. Illustration of MS to BS association for a network with 7 Base Stations, 3 sectors per base station and 42 mobile terminals distributed in a uniform random fashion.

1) Problem Formulation: In order to construct the interference graph a set of interferer nodes has to be defined for every mobile station i in the system. Let S_i be the useful signal received at a given station i. We define the problem such as

$$\begin{aligned} \forall i = 1..n \quad \text{minimize} \quad & P = \frac{S_i}{\sum_j I_{ij} x_j} \\ \text{subject to} \quad & \frac{S_i}{\sum_j I_{ij} x_j} \geq SIR_T \\ & x_j \in \{0,1\} \end{aligned} \tag{1}$$

where I_{ij} is the interference signal introduced by station j to station i, x_j is a binary value indicating whether I_{ij} has been selected and SIR_T is a minimum SIR predefined threshold for every station in the system. The goal in this case is finding the minimum possible number of interferers that need to be blocked from transmitting simultaneously such that the time-frequency reuse between cells can be maximized.

This problem is equivalent to the *Binary Knapsack Problem* extended to a *Subset-Sum Problem* which is NP-Complete [11] as proved next.

Theorem 1: Minimize P as defined in Problem (1) is NP-Complete.

Proof: Consider a system with n stations where the experienced SIR for every single station i should fulfill

$$\forall i = 1..n \quad \sum_j^n I_{ij} x_j \leq SIR^i \tag{2}$$

and $SIR^i = \frac{S_i}{SIR_T}$.

Combining the above with Eq.(1), the problem of minimizing P can be re-written as follows

$$\begin{aligned} \text{maximize} \quad & Z = \sum_j^n c_j x_j \\ \text{subject to} \quad & \sum_j^n w_j x_j \leq W \\ & x_j \in \{0,1\} \end{aligned} \tag{3}$$

where we assume $c_j = w_j = I_{ij}$ and $W = SIR^i$. Since Eq.(3) shows exactly the formulation of a *Binary Knapsack Problem* [12], we can state that the theorem has been proved. ■

Given that no scalable solution can be found for NP-complete problems, an heuristic solution is described next based on ICCS state-of-the-art solutions.

2) Heuristic Solution: As in well known approaches to construct interference graphs between network nodes [4], we consider the interference relations for a specific mobile terminal k and collect them in a set I_k. Note that independently of whether a specific transmission is directed to (downlink) or originated by a mobile terminal (uplink) interference graphs can be always constructed based on mobile terminals interference relations. Then, in order to determine the edges to be considered in the interference graph for a specific mobile terminal, either in the downlink or uplink direction, a given desired SIR threshold is defined SIR_T and the largest interferers from I_k sequentially removed until the worst-case SIR is above the specified threshold:

$$\frac{S_k}{\sum I_k} > SIR_T \tag{4}$$

where S_k corresponds to the received signal strength at mobile terminal k when it is served.

As a result of performing this process for all mobile terminals in the network, a non-directional interference graph is obtained where the degree of each vertex indicates the number of relevant interference relations for each mobile terminal. In general, the vertex degree is expected to be lower in areas with good reception conditions than in areas with worse ones.

As an example, in Figure 1 a network with 7 Base Stations, 3 sectors per base station and 42 mobile users distributed in a uniform random fashion is shown and their base station to mobile user association depicted with a link. Applying the process previously described to construct an interference graph based on Eq.(4), 129 interference relations (edges) are obtained in the downlink direction, see Figure 2(a).

Since the number of edges in an interference graph have a direct relation to the number of radio resources that can not be used *simultaneously*, in the following we consider the exploitation of application reservation information with the objective of reducing this number.

B. Interference Graph Reduction based on Reservations

ICCS solutions make resource assignment decisions based on the interference graph information derived as described in the previous section. In this paper we propose an enhancement to this approach by considering reservation information available in commonly deployed wireless technologies. This approach is based in our previous work in [13] which we summarize next for the convenience of the reader.

3GPP LTE/LTE-A and IEEE 802.16/16m networks support QoS reservation of resources by allowing new flows to apply for admittance in the system through request messages indicating their specific requirements. Such requests contain a set of QoS parameters which include different information depending on the service type. Table I shows an example

3GPP LTE QoS Parameters per Resource Type					
Res. Type	**QCI**	**Priority**	**Delay**	**Loss Rate**	**Service Ex.**
GBR	1	2	100 ms	10^{-2}	Voice
GBR	2	4	150 ms	$10^{-}3$	Live Str
GBR	3	3	50 ms	$10^{-}3$	RT Gaming
GBR	4	5	300 ms	$10^{-}6$	Buff Str
Non-GBR	5	1	100 ms	$10^{-}6$	IMS Sign.
Non-GBR	6	6	300 ms	$10^{-}3$	TCP-based
IEEE 802.16-2009 QoS Parameters per Data Delivery Service					
Data Delivery Serv.	**UGS**	**ERT-VR**	**RT-VR**	**NRT-VR**	**BE**
Min. Resv. Tr. Rate	●	●	●	●	
Max. Sust. Tr. Rate		●	●	●	●
SDU size	●				
Maximum Latency	●	●	●		
Tolerated Jitter	●	●			
Traffic Priority		●		●	●
Req./Trans. Policy	●	●	●	●	●

TABLE I
REQUIRED PARAMETERS FOR QOS SERVICES IN 3GPP LTE AND WIMAX

of different sets of QoS guarantees for Guaranteed Bit Rate (GBR) services and Non Guaranteed Bit Rate (Non-GBR) services as defined by 3GPP's LTE specification [14]. A similar set of QoS parameters are defined by the IEEE 802.16-2009 standard [15] as summarized also in Table I. [1]

Based on the aforementioned set of QoS guarantees of different wireless technologies, for each reservation i a minimum set of requirements can be defined for services with QoS guarantees as: given a starting time t_i, a certain amount of capacity B_i (bits) is reserved periodically for transmitting flow's i data within a time interval T_i. Such resource reservation requests can be modeled as a periodic discrete sequence of Kronecker deltas with amplitude B_i in the following way

$$B_i \cdot \delta_{t,t_i+n\cdot T_i} = \begin{cases} B_i & \text{if } t = t_i + n \cdot T_i \ ; \ n \in \mathbb{Z}_{\geq 0} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Data traffic not requiring stringent QoS guarantees and/or short-lived can still be accommodated with the proposed model by adapting the reservation lifetime and corresponding configuration parameters accordingly. Note that in the case of 3GPP LTE and WiMAX both uplink and downlink transmissions are always scheduled by the Base stations. Thus, the information required for their modeling is readily available.

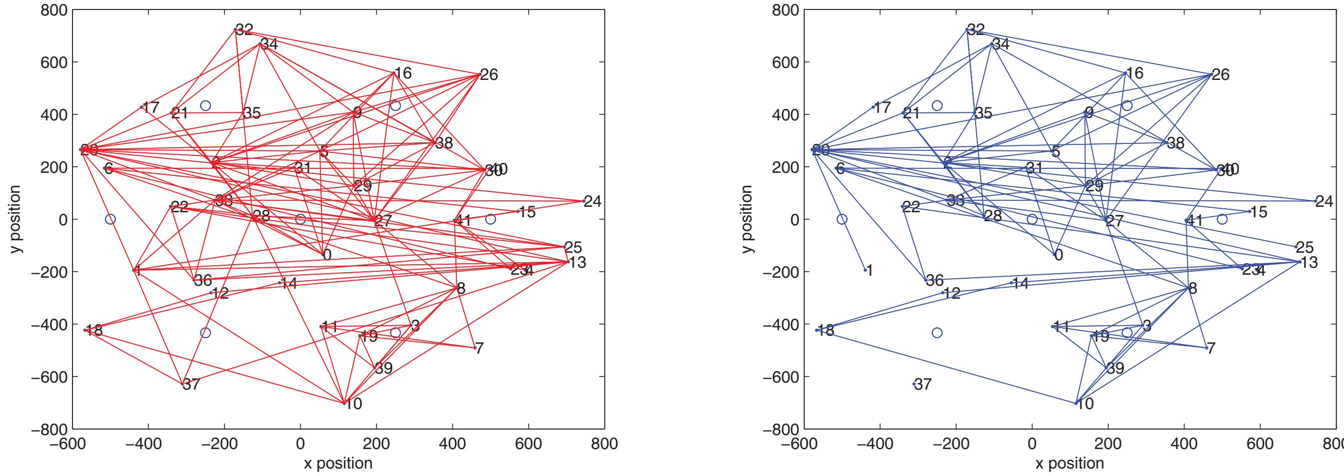
In [13] we considered the *Diophantine* solution for predicting intersections in the time domain between reservations. The *Diophantine* approach works as follows. Considering two flows already accepted in the system described with the resource reservations $B_i \cdot \delta_{t,t_i+n_i\cdot T_i}$ and $B_j \cdot \delta_{t,t_j+n_j\cdot T_j}$, an intersection will occur for the set of n_i and n_j combinations which fulfill

$$\{n_i, n_j \in \mathbb{Z}_{\geq 0} : t_i + n_i \cdot T_i = t_j + n_j \cdot T_j\} \tag{6}$$

Then, based on the linear diophantine equations theory, we know that there will be a set of integer solutions for n_i and n_j if

$$\frac{t_j - t_i}{d} \in \mathbb{Z} \tag{7}$$

[1]Note that in addition to the QoS requirements, the transmission schedule might be also influenced by power saving algorithms, see e.g. [16]. The extension of the modeling presented in this section to jointly deal with QoS and power saving algorithms is left as future work.



(a) ICCS

(b) RIA-ICCS

Fig. 2. Illustration of Interference Graph for a network with 7 Base Stations, 3 sectors per base station and 42 mobile terminals distributed in a uniform random fashion for ICCS and RIA-ICCS.

where $d = gcd(T_i, T_j)$ and gcd stands for greatest common divisor.

When the previous condition holds, the set of solutions corresponding to a specific pair of reservations can be found with the extended Euclidean algorithm. Readers interested in a detailed description of this process are referred to [13].

By applying the $Diophantine$ solution to all pairs of reservations in the system the potential intersections between all pairs of reservations can be found and structured in a matrix of intersections. In the rest of the paper this solution will be referred as *E-Diophantine*. The matrix of intersections information can be then exploited for reducing the number of edges in the interference graph previously obtained by simply removing all edges with no reservation intersection.

For illustration purposes, the reduced interference graph based on the previous network example and obtained by applying the *E-Diophantine* solution is shown in Figure 2(b) considering one reservation per mobile terminal and t and T randomly drawn from a uniform distribution between $[1, 100]$. In this particular case the number of interference relations has been cut down from 129 to 96 edges, i.e., $\approx 1/3$ reduction.

C. Resource Allocation Based on Reduced Interference Graph

Based on the reduced interference graph obtained, the resource assignment constraints can be derived considering that all connected mobile users can not be served simultaneously on the same set of resources. In order to minimize resource utilization, the problem can be formulated as finding the minimum set of disjoint resources fulfilling the interference graph constraints.

The generic formulation of this resource assignment problem falls into the problem space of graph coloring which has already been extensively studied in the past. Graph coloring problems are known to be NP-hard as proved in [11] and therefore, different heuristics have been defined to obtain a close to optimal solution at a reasonable computational cost. The actual solution to be used from the different options available depends on the desired accuracy and the actual hardware capabilities and thus, it is left out of the scope of this paper since the proposed reservation information aware interference graph reduction solution should be compatible with any graph coloring algorithm. For evaluation purposes though, in this paper a graph coloring resource assignment heuristic has been chosen, *Dsatur*, which was first described in [17] and has already been considered in related interference coordination approaches, see e.g. [4]. In the following we briefly describe our customization of the Dsatur solution to our case.

Dsatur defines for each vertex a *saturation degree*, corresponding to the number of different colors to which the vertex is adjacent to and sorts the vertices by decreasing degree order. The vertex with maximal degree is assigned the first color and the saturation degree for every vertex recomputed considering neighbouring colored vertices. The process is then repeated iteratively until all mobile users have been assigned a resource. In the application of *Dsatur* to our specific case, a modification has been introduced to improve performance. A *connection degree* metric was defined which reflects the number of edges connecting to a specific mobile user. With this metric, whenever the saturation degree is the same for several mobile users, the color assignment is performed according to a decreasing *connection degree* instead of randomly.

D. RIA-ICCS Contributions Beyond State-of-the-art

1) Multi-cell High-Level Scheduling Abstraction: The main novelty of the proposed RIA-ICCS approach is that by modeling the resource reservations with the *E-diophantine* solution, an a priori abstraction of the scheduling process impact on the interference graph edges can be performed. The abstraction of the scheduling process proposed imposes the requirement that the resource assignment performed has to necessarily conform to the model defined. However, note that although the model determines when the resource requirements of different reservations will coincide in time on a frame-by-frame basis, it allows flexibility on the amount of resources to be allocated. Therefore, the usage of usual utility-based scheduling policies taking advantage of varying channel conditions in time and considering the importance of the data to be transmitted according to Service Level Agreements is not prevented.

2) Interference Graph Size: Based on the scheduling abstraction, an interference graph with a reduced number of edges can be derived. Note that optimal or heuristic resource allocations solutions not considering an a priori modeling of the interrelation between reservations needs can not perform a reduction of the interference graph edges as the one allowed by our solution. Although an intercell coordinated scheduling controller might have access to Base Stations buffer occupancy and SLA information, if no a priori assumption of reservations intersection is done, the resource assignment process still would need to consider the full interference graph for the reservations not yet allocated since the resource scheduling decision for these reservations has not been taken yet.

3) Computational Load: Multi-cell ICCS solutions could consider performing the resource scheduling for all BSs under the ICCs controller prior to the radio resource assignment. However, this would be a very expensive process in computational load terms likely to become unfeasible for large network sizes. The modification of the interference graph *during* the resource allocation process could be also considered by an optimal solution but it would require to re-evaluate previous assignments, incurring in an exponential computational load increase. Heuristic solutions taking resource allocation decisions sequentially would not be able to reduce the interference graph size at the same level as RIA-ICCS since non-allocated reservations could still be allocated within the same frame as long as there is capacity left.

4) Resource Utilization Efficiency: The reduction of the number of edges in the interference graph of ICCS solutions directly translates in a lower blocking probability of the resource assignment process. Thus, the efficiency usage of the radio resources can be increased resulting in a higher system capacity. The gain achieved with RIA-ICCS though depends on the intersection probability of resource reservations between interferers. The lower the intersection probability, the higher the gain. However, this intersection probability is not out of the control of the network operator since it decides the actual translation of the resource reservation requirements to the actual multi-cell high-level scheduling abstraction.

IV. Performance Evaluation & Discussion

The objective of the RIA-ICCS approach presented in this paper is to exploit resource reservation information available in cellular networks to enhance the performance of ICCS state-of-the-art solutions. In this section we evaluate the performance improvement obtained by simulation and focus on two major ICCS generic metrics: number of edges in the interference graph and resource allocation blocking probability.

A. Simulation Setup

Our results are obtained using a system-level simulator which has been calibrated against the channel models defined by IMT-Advanced [18]. The scenario described in the previous section is considered which consists in 7 base stations having 3 sectoral antennas depicted in Figure 1. Mobile users are randomly dropped in the covered area and assigned according to their pathloss to the corresponding base stations sectors. The number of mobile users in the system ranges from 63 to 357 in order to cover both the non-saturated and saturated resources cases. The detailed system parameters configuration is summarized in Table II.

Parameters	Values
Environment	1 Tier, 7 BSs with 3 Sectors
Frequency Reuse	1
Physical Scenario	IMT Urban Macro
Users distribution	Uniform
Users association type	Strongest Signal
Interference Graph Threshold	-2 dB
Number of TX antenna per BS	4
Number of beams	4
Number of RX antenna per MS	2
Number of spatial streams	2
Number of LRUs per DL Subframe	24
Time duration Frame	5 ms
Number of subcarriers	24
Channel Bandwidth	10 MHz
Shadowing Model	Spatial Correlated
Effective SNR Abstraction	Mean Abstraction

TABLE II
ITU IMT-Adv Simulation Parameters Configuration

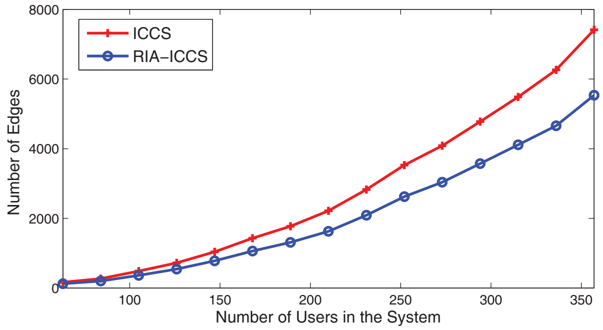
The resource reservation information for the different mobile users is modeled according to the description provided in Section III-B in the following way. Each mobile station is associated with a resource reservation whose starting time t_i and random period time T_i is randomly chosen from a uniform distribution [10,100] and the value B is fixed. Then, the corresponding reservation intersection matrix between every pair of reservations is constructed. Finally, in the RIA-ICCS case, the *E-diophantine* solution is applied and the reduction of the number of edges in the interference graph performed.

B. System Performance

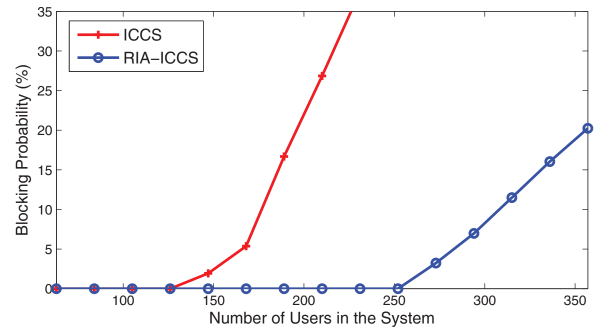
The core of ICCS solutions is based on the interference graph concept. Therefore, the number of edges in the interference graph is a key metric when comparing different ICCS approaches as it has a direct impact on their performance.

In Figure 3(a) the number of edges in the interference graph for the ICCS and the RIA-ICCS solutions is shown. As it can be observed, as the number of mobile stations in the system grows, an increasing reduction in the number of edges is achieved, reaching for instance 33% in the 357 MSs case. The trend is as expected since, given our generic reservation model were the t_i and T_i values are randomly drawn, some of the reservations do not coincide in time. Thus, more edges can be removed from the interference graph as the number of reservations grows. The actual reduction though depends on the reservations intersection probability. The higher the probability of intersections, the lower the achievable benefit with RIA-ICCS.

The corresponding results in terms of resource allocation blocking probability are shown in Figure 3(b). In this case, for fairness reasons the same resource allocation algorithm is applied to both approaches, Dsatur, described in Section III-C. The figure shows the advantages of the proposed RIA-ICCS solution as compared to ICCS. ICCS starts experiencing



(a) Number of edges in the Interference Graph



(b) Blocking Probability

Fig. 3. Performance evaluation of RIA-ICCS benefits.

blocking during the resource allocation process from 126 MSs on while RIA-ICCS reaches this point at 252 users in the system. The trend is again as expected. As the number of resources required by the reservations in the system grows, the blocking probability also grows according to the number of interference graph edges. In the RIA-ICCS case, since the number of edges is lower, reservations start to get blocked for a higher number of MSs in the system than for ICCS and the slope increases at a slower pace.

Based on the results we can conclude that the exploitation of reservation information in ICCS solutions can be effectively used to reduce the number of edges to be considered in an interference graph. Moreover, the reduction grows as the number of reservations increases providing the larger benefits when the system needs it most.

V. Summary & Conclusions

Intercell interference is a major limiting factor for fulfilling ITU's IMT-A requirements in future wireless networks. Different solutions are being considered to address this challenge. Among them, intercell coordinated scheduling (ICCS) arises as a promising one able to increase the spectral efficiency of future systems at an affordable inter-BS communication cost. In this paper we have presented our proposed Reservation Information Aware Intercell Coordinated Scheduling (RIA-ICCS) solution which considers application reservation information when constructing an interference graph for ICCS purposes.

Based on the results presented we can conclude that i) RIA-ICCS allows to significantly reduce the number of edges in an interference graph for ICCS solutions and its benefit increases as the number of mobile stations grows, i.e., when the system needs it most and ii) the reduced number of edges in the interference graph can be effectively translated to a lower blocking probability using state-of-the-art resource allocation algorithms.

Thus, the consideration of resource reservation information can be effectively exploited for ICCS solutions to increase the system radio resource utilization efficiency. The actual efficiency gain depends on the intersection probability in time of reservations from different interferers, which can be controlled by a network operator.

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