Interference management techniques like inter-cell interference coordination (ICIC) will play a key role in enabling high spectral efficiency in future wireless OFDMA-based cellular systems. The aim of ICIC is to lower inter-cell interference by coordinating the usage of spectrum resources among neighboring cells. Especially for the cell-edge users, avoiding the reuse of the same resources in neighboring cells yields a significant increase in SINR and thus capacity. In this paper, we consider decentralized ICIC schemes for the uplink of an LTE system in which base stations perform selfish resource allocation decisions. System level simulations in a multi-cell scenario show the convergence of the distributed schemes towards Nash equilibria. The mean cell throughput as well as the 5% CDF user throughput are compared to those achieved by frequency reuse 1 and 3 deployments. The simulation results show that the proposed schemes adapt well to varying uniform and especially non-uniform traffic loads.

I. INTRODUCTION

Inter-cell interference coordination (ICIC) has been included as a Radio Resource Management (RRM) aspect of UTRAN Long Term Evolution (LTE) since Release 8 [1]. The aim of ICIC is to lower inter-cell interference by coordinating the reuse of spectrum resources which are called physical resource blocks (PRBs) in LTE. A reduction of inter-cell interference can be achieved by using only a subset of the total system-wide resources in each cell. The resulting lower interference per PRB allows a higher capacity per resource. However, the lower number of available PRBs per cell reduces the total capacity so that the total cell capacity depends on the trade-off between lower interference and higher resource availability.

Of course, a reduction of interference by restricting the usage of PRBs is only achieved if neighboring cells reuse the spectrum in a coordinated way. A traditional static coordination scheme (reuse 3) consists of forming cell clusters of 3 cells that each use a different third of the resources. It achieves a good coordination of resources and thus low inter-cell interference but drastically limits peak data rates and cannot adapt to varying traffic load between cells. Therefore, LTE in principle allows a full reuse (reuse 1) of resources but cannot adapt to varying traffic load between cells. Especially for the cell-edge users, avoiding the reuse of the same resources in neighboring cells yields a significant increase in SINR and thus capacity. In this paper, we consider decentralized ICIC schemes for the uplink of an LTE system in which base stations perform selfish resource allocation decisions. System level simulations in a multi-cell scenario show the convergence of the distributed schemes towards Nash equilibria. The mean cell throughput as well as the 5% CDF user throughput are compared to those achieved by frequency reuse 1 and 3 deployments. The simulation results show that the proposed schemes adapt well to varying uniform and especially non-uniform traffic loads.

II. SELFISH INTERFERENCE COORDINATION BY eNBs

The presented hierarchical resource allocation process separates the decisions which PRBs are available in each cell from the scheduling of users onto resources. That way, suitable frequency-selective schedulers can still realize a (somewhat reduced) multi-user diversity gain while enjoying reduced interference levels at the same time.
A. Non-cooperative game model

Both schemes are based on a non-cooperative game model [4] in which the eNBs as the players strive to selfishly select a subset of PRBs that offers them the highest utility – in this case the lowest interference. The schemes differ in the way how the eNBs obtain their knowledge of the current interference situation.

We denote the choice of player \( i \) by the binary vector \( x_i \in \mathbb{R}^m \) with \( x_{i,k} = 1 \) meaning that PRB \( k \) is among the chosen subset of the \( m \) PRBs available in total in the system. Depending on its own decision \( x_i \) and the selection of all other eNBs denoted by \( x_{-i} \), an eNB will experience a certain interference situation \( \hat{I}_{i,k}(x_{-i}) \) for each PRB \( k \) that it uses.

Note that the actual interference per PRB in the uplink of an actual multi-cellular system will not only depend on the subsets used in other cells but also on the UE scheduling at a specific time instant. The experienced inter-cell interference can differ significantly depending on whether a center-cell UE with low transmit power or a cell-edge UE with high power was scheduled in a neighboring cell. In the following, we will assume that we can nevertheless express PRB \( k \)'s utility to player \( i \) by assuming a certain interference situation \( I_{i,k} \) solely based on the PRB allocations \((x_i, x_{-i})\). Our simulation results show that this assumption is justified.

We express the utility of an eNB obtains from its own allocation \( x_i \) while experiencing the interference caused by the other cells' allocations \( x_{-i} \) as \( U_i(x_i, x_{-i}) = -\sum_{k=1}^{m}x_{i,k}I_{i,k} \). To avoid the trivial solution \( x_i = 0 \), we require each eNB to allocate a fixed number \( D_i > 0 \) of resources. In lowering their own experienced interference, the players will try to avoid allocations of other players leading to an anti-coordination game.

If the interference from cell \( j \) in cell \( i \) equals the interference cell \( i \) causes to cell \( j \) on some PRB \( k \), the interference situation is symmetric and the game can be shown to admit a potential function \( \Phi(x_i, x_{-i}) \) [4]. In this case, the game will have one or multiple Nash Equilibria (NEs) \((x_i^*, x_{-i}^*)\) [7]. These NEs present stable system-wide resource allocations because no player has an incentive to deviate from his chosen allocation \( x_i^* \) assuming all other players keep their allocations \( x_{-i}^* \) constant.

Reaching such a stable allocation is highly desirable, however, collectively agreeing upon a specific Nash equilibrium is difficult for the players because, for combinatorial reasons, there will be many different Nash equilibria with possibly equal utilities. Thus, players trying to reach a common NE cannot know in advance which one to aim for. In such situations, players can sometimes agree upon or learn [8] a common NE by playing many successive rounds of the game. For potential games, it can be easily shown [4] that sequential unilateral best-response adaptations to the previous player's move will ultimately lead to a NE.

B. Simultaneous adaptation algorithm

The adaptation algorithm for both of our schemes employs such a best-response approach but allows for simultaneous re-allocations. In contrast, the above-mentioned learning approach allows only one adaptation at a time. This avoids situations in which multiple eNBs choose the same low-interference PRB but does not allow for fast convergence in large scenarios. We thus proposed an algorithm [4] that de-facto always converges under simultaneous adaptations by including a better PRB only with some probability \( P_{sel} \). If chosen correctly, on average only one eNB in a neighborhood will switch to a better resource so that conflicts creating high interference are avoided.

The eNBs in our simulations periodically check each radio frame if some PRB \( k \) of their \( D_i \) PRBs could be replaced by another one that now has lower interference based on the latest interference information \( \hat{I}_{i,k} \). If this is the case, the PRB is replaced by the better one with probability \( P_{sel} = 0.1 \) but only if the interference is lower by some threshold \( \Delta I \). The latter check helps to make the interference situation as stable and predictable as possible by avoiding small-scale fluctuations.

Due to the probabilistic element, the convergence cannot be guaranteed for this scheme but in practice it always converges with much higher speed than a sequential solution, see [4].

III. PROPOSED SCHEMES

We now introduce the two concrete schemes that will be evaluated in Section V. They both follow the general scheme outlined above but differ in the way they obtain the interference information \( \hat{I}_{i,k} \). The advantage of the first scheme is that it does not rely on any inter-cell signaling to determine \( \hat{I}_{i,k} \). However, its convergence cannot be guaranteed. On the other hand, the second scheme provably converges but needs inter-cell signaling to do so. The algorithmic complexity of both schemes is very low. The eNBs just need to identify the PRBs with the lowest interference by sorting them according to \( \hat{I}_{i,k} \). The update of the allocated PRB subset can then be performed in a single loop replacing current PRBs with better but previously unused PRBs (subject to the interference threshold \( \Delta I \) and the selection probability \( P_{sel} \)).

A. Autonomous scheme

In this scheme, we assume that the eNBs periodically measure the interference across all PRBs themselves. As they are the target receivers for all uplink transmissions, no signaling between eNB and UEs is involved. Also, no communication with other eNBs is necessary allowing for completely autonomous operation.

As mentioned above, the inter-cell interference not only depends on the PRB allocations in neighboring cells but also on the user scheduling yielding a high variance. To combat these fluctuations we measure the current actual interference \( I_{i,k,t} \) on all PRBs every 10 ms radio frame and derive an exponentially averaged value \( \hat{I}_{i,k,t} = \alpha I_{i,k,t} + (1-\alpha)\hat{I}_{i,k,t-1} \).

In our simulations, \( \alpha = 0.005 \) and an interference threshold of \( \Delta I = 1 \) dB have yielded both good performance and convergence behavior.

As mentioned in Section II, the interference coordination game has a potential and thus a NE if interference impacts between cells are symmetric. However, this is in general not
The ICIC schemes shall adapt to traffic and UE mobility and consequently operate on timescales of seconds to hours. We therefore do not consider small-scale effects like fast fading. We only model pathloss, see Table I. To evaluate the achievable throughput depending on the received Signal to Interference and Noise Ratio (SINR), denoted by $\gamma$, we use a model from [9] that assumes an implementation loss of 60% compared to Shannon’s capacity bound $S(\gamma) = \log_2(1+\gamma)$. It further requires an SINR of $\gamma > \gamma_{min} = -10$ dB and imposes an upper limit of 2.0 bps/Hz of spectral efficiency provided by the actual modulation and coding schemes, cf. (1).

$$Th[\text{bps/Hz}] = \begin{cases}
0 & : \gamma < \gamma_{min} \\
\alpha S(\gamma) & : \gamma_{min} < \gamma < S^{-1}(Th_{max}) \\
Th_{max} & : \alpha S(\gamma) \geq Th_{max}
\end{cases}$$

(1)

Uplink transmissions are power controlled in LTE. We model the open-loop power control scheme as defined in [10] [11], cf. Table I for details.

An exemplary scenario snapshot is shown in Fig. 1. We assume 27 eNBs each covering a 120° sector. Within these cells UEs are dropped at uniformly chosen random positions. To investigate the behavior with uneven UE distributions, between 0% and 80% of UEs are relocated among random cell pairs. The same algorithms are performed in each cell with the same level of detail. However, only the results from the shaded center cells are evaluated. No mobility is considered but different random drops are realized for every simulation run.

In the system and in every cell there are 36 PRBs with a bandwidth of 180 kHz each available for uplink transmissions. Every transmission time interval (TTI) of 1 ms we assign each UE to a PRB unless there are more users than PRBs. This implies that we do not consider throughput requirements for individual UEs as every UE gets at most one PRB yielding an SINR-dependent throughput. Thus, the number of UEs per cell determines the traffic load of that cell. It also determines the number of PRBs the ICIC coordination scheme selects for use in that cell. Note that the reuse 1 scheme does not impose any restrictions so that all 36 PRBs are available. The reuse 3 scheme avoids PRB reuse within the cell cluster and makes 12 PRBs available in each cell.

Due to a lack of mobility, the number of UEs per cell will remain fixed and consequently the number of allocated PRBs will be constant. However, the mapping of UEs to PRBs will be randomly permuted each TTI. That way, we model the effect of a frequency-selective scheduler on the assignment of PRBs to UEs. This has two consequences: First, it results in highly varying inter-cell interferences as interferences on a PRB $k$ might come from completely different origin UEs in a neighboring cell. This makes adapting to the inter-cell interference situation difficult for our autonomous scheme. Second, this improves the performance of the reuse 1 scheme as the used PRBs are always spread out over all 36 PRBs causing a kind of interference averaging effect.

**IV. PERFORMANCE EVALUATION FRAMEWORK**

In order to evaluate the performance of the two schemes compared to standard schemes like reuse 1 and reuse 3, we conducted system level simulations in a multi-cell scenario. As the main focus is on evaluating the ICIC schemes and how they trade-off resource availability against interference level, we do not model packet-based traffic or the LTE protocol stack in detail.
TABLE I
OVERVIEW OF RADIO SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>2000 MHz</td>
</tr>
<tr>
<td>Number of PRBs</td>
<td>36</td>
</tr>
<tr>
<td>Bandwidth per PRB</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Thermal noise power</td>
<td>-121 dBm per PRB, 5 dB noise figure</td>
</tr>
<tr>
<td>eNB Antenna pattern [12]</td>
<td>$A(\Theta) = \min { 12 \left( \frac{\Theta}{\Theta_{\mathrm{min}}} \right)^2, A_{\text{min}} }$</td>
</tr>
<tr>
<td>Scenario size</td>
<td>1500 m x 1500 m</td>
</tr>
<tr>
<td>Number of eNBs</td>
<td>27 (9 sites with 3 cells/sectors each)</td>
</tr>
<tr>
<td>Number of UEs</td>
<td>10, 20, or 30 with 0% to 80% relocated between random cell pairs</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Pathloss model [12]</td>
<td>$L = 128.1 + 37.6 \log_{10}(R[\text{km}])$</td>
</tr>
<tr>
<td>Max. Tx Power in UL</td>
<td>$P_{\text{max}} = 23$ dBm per PRB</td>
</tr>
<tr>
<td>Uplink power control</td>
<td>$P = \min(P_{\text{max}}, P_0 + \alpha L)$ per PRB with $P_0 = -48$ dBm and $\alpha = 0.7$</td>
</tr>
<tr>
<td>Link-level performance</td>
<td>see equation (1) with these parameters: $\alpha = 0.4$, $\gamma_{\text{min}} = -10$ dB, $T_{\text{max}} = 2.0$ bps/Hz</td>
</tr>
<tr>
<td>Simulation time</td>
<td>5 seconds with 3 seconds transient phase</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS

System level simulations have been performed using the openWNS simulator [13]. For each combination of ICIC schemes including reuse 1 and reuse 3, number of UEs, and degree of uneven UE distribution, results are merged from the simulation of 8 random topologies.

A. Convergence of Decentralized Coordination

Figure 2 shows the convergence behavior of the dynamic schemes during a representative simulation run. The y-axis gives a measure of how many PRBs are still seen by the algorithms as more favorable (in terms of interference) to be used by the respective eNBs, than the currently assigned PRBs. The signaling-based scheme fully converges in a very short time. The autonomous scheme also starts converging very fast, however, not completely so. Due to the asymmetry of the interference impact and the memory of the exponential averaging, slight changes in the observed interference remain. However, instability is easily avoided by the applied interference threshold.

B. Performance under different traffic loads

A comparison of the mean cell throughput over 8 random drops is provided in Figures 3(a) through 3(c) as a function of the standard deviation of the number of users per cell, i.e., as a function of the spatial inhomogeneity of the traffic. From Fig. 3(a) we observe that in the homogeneous case (exactly 10 users per cell, std. dev. = 0) reuse 3 actually provides the best results because it guarantees low inter-cell interference, while the fixed number of 12 PRBs per cell is sufficient to serve the 10 users. When the traffic inhomogeneity grows beyond a standard deviation of two users from the mean, the performance of the reuse 3 scheme starts to degrade because the likelihood grows to have a higher number of users in one cell than PRBs available. In comparison, the reuse 1 scheme has always enough PRBs available, however due to the lack of coordination between neighboring cells, the inter-cell interference limits the throughput. The two dynamic schemes perform very similar to each other, starting only slightly worse than the reuse 3 scheme. With growing traffic inhomogeneity the benefit of the adaptive nature of these schemes becomes evident from the fact that their performance hardly degrades with growing standard deviation of the number of users. Beyond a standard deviation of two users per cell, the dynamic schemes perform better than both fixed schemes. When the overall traffic grows to a mean number of 20 users per cell (Fig. 3(b)), reuse 1 and reuse 3 switch positions, i.e. reuse 1 starts performing better than reuse 3. This is due to the fact that reuse 3 is now permanently suffering from a low number of available PRBs in comparison to the number of users per cell. The dynamic schemes adapt to the growing traffic as well as to the inhomogeneity and thus perform better than the fixed schemes, throughout. Finally, when the system load further grows (Fig. 3(c)), the performance of the reuse 1 scheme approaches that of the dynamic schemes, since the number of users per cell is becoming similar to the number of PRBs available to the system, limiting the potential of coordination for the dynamic schemes.

Figures 4(a) through 4(c) show the 5% CDF cell throughput for the different scenarios, reflecting mainly the performance of the cell edge users who are suffering from low SINR. The relative behavior of the compared schemes is very similar to that of the mean cell throughput. Comparing the overall performance of all schemes, we can observe that the average cell throughput will grow with increasing traffic, while the performance of the cell-edge users degrades, as expected.

C. Comparison of dynamic schemes

The performance of the two dynamic schemes is almost identical. This means that the autonomous scheme adapts well to the real interference situation yielding a significant reduction even when it does not completely converge (cf. Fig. 2). On the other hand, the complete convergence of the inter-cell signaling based scheme does not contribute a significant additional improvement as its virtual interference scenario does not exactly reflect the actual interference situation.
In this paper, we introduced low-complexity decentralized resource allocation schemes aiming at interference coordination among cells in future wireless networks. Through system simulations we could show that the dynamic schemes converge well. In contrast to fixed reuse, the proposed schemes adapt to changing traffic loads and specifically to inhomogeneous traffic situations, providing almost in all cases the best throughput in comparison. Comparing an inter-cell signaling based scheme and a completely autonomous scheme we could show that the latter might not fully converge but offers the same performance without any signaling between cells. This is remarkable because it allows the implementation of effective dynamic inter-cell interference coordination mechanisms without introducing standardization requirements. Future work will focus on further improving the proposed schemes as well as on investigating the performance using a full LTE protocol stack.

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**REFERENCES**


