Self-Organizing Coalitions for Conflict Evaluation and Resolution in Femtocells

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Abstract—The recent introduction of carrier aggregation in LTE-Advanced enables new possibilities in designing frequency domain interference reduction and management schemes. These methodologies are of extreme interest in the case of dense and uncoordinated deployments of femtocells. In such scenarios, dense deployment of cells coupled with the scarcity of frequency resources may lead to a potentially disruptive amount of interference, which severely affects the performance of the system. This contribution presents a novel method inspired by graph and coalitional game theories. The proposed algorithm consists of a set of distributed and scalable rules for building coalitions; these rules essentially resolve the conflicts among avid femtocells competing for a limited amount of resources. The proposed scheme has been designed by targeting localized reconfigurations, thus avoiding reconfiguration storms in the network. Furthermore, the rules governing the resource redistribution ensure overall system performance improvements while maintaining a certain degree of fairness among the competing nodes. Simulation results prove the effectiveness of the proposed method.

Index Terms—Spectrum Sharing, Coalitions, Femtocells, LTE-Advanced, Self-organizing.

I. INTRODUCTION

Carrier aggregation, i.e., simultaneous transmission over multiple component carriers, is emerging as a key feature of future wireless communication systems aiming at fulfilling the targets set by the International Telecommunication Union in [1]. It offers the possibility to increase physical layer data rates proportionally to the number of aggregated carriers and facilitates backward compatibility at the same time. Today, carrier aggregation is already present in the form of channel bonding (two adjacent carriers) in WiFi (IEEE 802.11n) and it is a central element of both LTE-Advanced and WiMAX (IEEE 802.16m), currently under standardization.

A side benefit of carrier aggregation is the potential to dynamically reconfigure the system bandwidth, which can be exploited in the form of simple yet effective frequency domain interference coordination schemes. This becomes especially attractive when one considers future deployments of femtocells. These are cost-effective, user-deployed, low-power base stations operating in licensed spectrum. The concept is extremely enticing due to the potential benefits that it offers to operators and end-users, e.g. improvement of indoor broadband wireless services and offload of the macro-cellular network [2], [3]. Nonetheless, unlike carefully planned macro cells, femtocell deployment will be uncoordinated and potentially chaotic. For that reason, femtocell deployment demands some form of interference management [4], [5].

In order to cope with the traffic demand, heavily loaded cells will need more component carriers than lightly loaded ones. Under low to moderate load conditions, a simple “first-in, first-served” mode of operation may be effective. In this case, the inherently time-varying nature of traffic in each cell will help accommodate the demand for extra component carriers. However, in high load situations the competition among neighboring cells can force them to engage into mutually destructive behavior through greedy/blind competition for the same resource. This can lead to severe inequities or result in an inefficient usage of the resources due to excessive interference levels, especially within dense local area network deployments.

In the following, we propose a practical and self-organizing method aiming at fair and efficient resource distribution whenever competition for the same resource arises among two or more cells. The main objective is to ensure access to additional resources in a rational and coordinated fashion. Our case study is based on LTE-Advanced, whose terminology is employed; nonetheless the proposed methodology is general and can be applied to other radio access technologies. The considered target deployment scenario is a dense-urban residential one, assuming a closed subscriber group access policy. We derive our results from a Monte Carlo performance evaluation according to the methodology defined in [6] by 3GPP.

The rest of this paper is organized as follows: Section II points to related research in the literature and introduces the proposed concepts in the detail. Section III states the simulation assumptions, while Section IV presents and discusses the obtained results. Finally, Section V concludes the paper and points out possibilities for future work.

II. SYSTEM MODEL

In this section we introduce our framework and carefully describe the proposed method — Self-Organizing Coalitions for Conflict Evaluation and Resolution (SOCCER). Due to space limitations, a rigorous mathematical analysis is beyond the scope of this short contribution and it will be the subject of a future paper. We point interested readers to the pertinent literature on coalitional game theory [7] and we provide a quantitative proof of SOCCER effectiveness by means of numerical simulations.
A. The proposed framework

We define a network as a set of $N$ femtocells, denoted by $\mathcal{N} = \{1, \ldots, N\}$ (home eNBs (HeNBs) in LTE-Advanced terminology), which operates in a licensed spectrum. The spectrum is divided into a set of Component Carriers (CC), $\mathcal{M} = \{1, \ldots, M\}$ of cardinality $|\mathcal{M}| = M$, each of bandwidth $BW_{\mathcal{m}}$, $\mathcal{m} \in \mathcal{M}$. CCs can be either contiguous or not. The framework is depicted in Fig. 1 along with a simplified representation of the system showing a coalition formed by two HeNBs. We discuss coalitions in detail in the next two sections. In the example, the total bandwidth is equally divided into 3 CCs and as soon as the requirements of each cell can no longer be met with a single CC, a conflict of interest arises. Under such circumstances, it is highly desirable to ensure that this resource is utilized in an efficient and fair manner. This task can be accomplished by forming coalitions.

We posit that coalition managers, local to each HeNB, keep coalition tables, one for each shared CC. This table stores the list of current coalitions and the corresponding allocation restrictions. We also suggest that Radio Resource Management (RRM) entities such as packet schedulers interact with coalition managers indicating the need for CCs subject to local traffic requirements. Additionally, coalition formation is binding, meaning that HeNBs must respect the agreement and packet schedulers shall abide to the imposed restrictions. Furthermore, it is relevant to stress: (i) coalition managers operate on a much longer time scale when compared to packet schedulers; (ii) the proposed multi-layered approach is not limiting; the coalition based concept can be employed both to intra- or inter-component carrier levels. Figure 1 depicts coalitions within (intra) CCs, however, if so desired, the entire system bandwidth can be seen as a single wideband resource to be shared via coalitions as seen in Section III.

In the following section we describe a set of distributed rules enabling the autonomous formation of coalitions among HeNBs, which can then be mapped into undirected graphs as explained in Section IV-B. The formation rules rely on simple capacity estimations based on prior system performance characterization and knowledge of mutual interference coupling between a pair of cells.

B. Strong bonding

The two central pillars of the proposed method are: determining the presence of strong bonding between pairs of HeNBs and the subsequent formation of coalitions following certain working principles. This section dissects strong bonding, while the coalitions are the subject of the next one. In simple terms, the presence of a strong bonding between two HeNBs implies that mutual cooperation by means of a coalition is beneficial. Conversely, in the absence of strong bonding, competition is fruitful and no restrictions are enforced.

Strong bonding is determined by a bidirectional relation between two HeNBs. This evaluation relies on so-called Background Interference Matrices (BIM) [4], which we postulate to be built by each HeNB based on standard downlink (DL) measurements, namely User Equipment (UE) Reference Signal Received Power (RSRP) [8]. Figure 2 illustrates the concept and depicts all involved links in the description that follows. Each UE measures the RSRP from both its serving cell and neighboring HeNBs, just as in handover measurements. The RSRP values are reported to its serving HeNB. In turn, the corresponding HeNB gathers this information and calculates differences of RSRP values (in dB). This calculation yields potential DL incoming C/I ratios in case the same CC is reused by the neighboring cell, as perceived by each of its served UEs. Clearly, there are many possible manners to utilize this knowledge, but in the context of femtocells we take the lowest C/I ratio reported towards a given neighbor as representative of the interference coupling between a pair of cells, henceforth denoted by $DL_{\mathcal{m}}(\cdot|\cdot)$. Naturally, if the femtocell serves more than a single UE, the lowest C/I value for different neighbors can come from different UEs. In such a way, interference coupling among cells is quantified on a pair-wise basis, i.e. not considering the total effectively received interference power. In addition to incoming ratios, DL outgoing C/I ratios (calculated as incoming ratios by neighboring cells) are signaled back and represented here by $DL_{\mathcal{m}}(\cdot|\cdot)$. The BIM information essentially “teaches” each cell about its mutual interference coupling with neighboring cells, which makes them capable of estimating the impact of any new allocation on surrounding cells, both as victims and sources of interference.

Now, let two neighbor HeNBs be denoted by $A$ and $B$. Mathematically, a strong bonding occurs whenever (1) is satisfied,

$$v(G_{\{A,B\}}) > v(G_{\{A\}}) + v(G_{\{B\}}) \quad (1)$$
where $v(G_{(A)})$, $v(G_{(B)})$ are the values of the single element coalitions, while $v(G_{(A,B)})$ is the value of a coalition formed by $A$ and $B$ in terms of Spectral Efficiency (SE in bits/s/Hz):

$$v(G_{(A)}) = SE[(C/I)_{A|B}]$$

(2)

$$v(G_{(B)}) = SE[(C/I)_{B|A}]$$

(3)

$$v(G_{(A,B)}) = \frac{1}{2} \cdot \{SE[(C/I)_{A}] + SE[(C/I)_{B}]\}$$

(4)

The function $v(.)$ is expressed by an adjusted Shannon capacity formula [9] based on a priori characterization of link level performance, where the bandwidth and the SNR efficiencies of the system are taken into account. It maps the potential C/I (taken from the BIM, such that $(C/I)_{A|B} = \min(DL_{(A)} \rightarrow \{B\}, DL_{(A)} \rightarrow \{B\})$) into spectral efficiency estimations. Moreover, while in (2) and (3) it is assumed that both nodes decide to simply reuse the entire resource, in (4) each HeNB gets one orthogonal half of the resource, which takes a sensible and fair non-aggression pact as a model.

Note that the information both cells see is identical given the way the BIM is created. Obviously, this is a compromise in order to avoid additional signaling and any information mismatch. It implies that any externalities are not considered while determining strong bonding. This simplification entails that we assume $(C/I)_{B|A} = (C/I)_{A|B}$ instead of using $(C/I)_{A|B}$ and $(C/I)_{B|A}$ in (2) and (3). Additionally, if the other cell is not present (made orthogonal), the channel is estimated to be free such that $(C/I)_{A} = (C/I)_{B} = (C/I)_{\text{free}}$ in (4). At the expense of additional signaling, the estimated C/I given the rest of the network $((C/I)_{\setminus A})$ that is currently using the same resource could be considered as well.

C. Formation rules

A coalition of otherwise interfering HeNBs is merely a code of conduct, which once established via bi- or multilateral agreements, dictates how its members shall share resources targeting resource orthogonalization. As such, a HeNB may be part of none, one or several coalitions at the same time. Furthermore, coalitions can be formed in different and independent ways on each CC. The cardinality of a coalition is the number of involved parts. We will use the notation $n$-coalition for a coalition of cardinality $n$.

Hereafter, a HeNB seeking for an additional CC is denominated a new entrant HeNB. The new entrant HeNB needs to determine which neighboring HeNBs should be considered as coalition candidates. Each candidate HeNB should fulfill two conditions: it is already using the desired CC and it has a strong interference bonding with the new entrant, as defined in (1). If there are no candidates, the solution is trivial: the new entrant HeNB can use the whole CC.

In order to reduce the complexity of the method, we consider here the case where the new entrant HeNB will send Coalition Formation Requests (CFR) for at most two coalition candidates. In Section IV-B we justify this choice, considering typical deployment scenarios. Then, the method can be implemented using six simple formation rules, depending on two aspects:

- Whether there is one or two coalition candidates.
- Whether the candidates are already involved or not in previously formed coalitions.

The formation rules can be summarized as follows:

1) Only one coalition candidate: There are two sub-cases:

- If the coalition candidate has full allocation of the CC, the resources shall be equally divided. Therefore, both the new entrant and the coalition candidate will have different halves of the CC, precisely as in Fig. 1.
- If the coalition candidate is already involved in other coalitions it will not have full allocation of the CC. In this case, the new entrant can use all the sub-resources which are not already allocated by the coalition candidate. Note that, in this case the new entrant may have even more than half of resources, characterizing a “free rider” situation, illustrated in Fig. 3a. If the coalition candidate has more than or exactly half the resources, then each of the parts shall allocate half of the resources.

2) Two coalition candidates: Here, there are four sub-cases:

- The coalition candidates are part of a 2-coalition. In this case, the resources shall be divided equally amongst the...
three HeNBs, augmenting the 2-coalition to a 3-coalition as shown in Fig. 3b.

- The coalition candidates are part of one or more 3-coalitions with third party HeNBs. In this case, the new entrant has to allocate exactly the same resources as the third party, and no changes are made to the resource allocation of the candidates. A new 3-coalition is formed amongst the three involved parts, as exemplified in Fig. 3c.

- The coalition candidates are not part of the same coalition and their allocations can be made compatible with the new entrant allocating half of the resources. In this case, the new entrant will form 2-coalitions with both of them and will allocate half of the resources on the most efficient fashion. One example is illustrated in Fig. 4a.

- The coalition candidates are not part of the same coalition but their allocations can not be made compatible with the new entrant allocating half of the resources, due to restrictions imposed by other coalitions previously formed. In this case, the new entrant will form 2-coalitions with both of them, but the CC will be divided in the same way as if there was a 3-coalition, i.e., in three equal parts, as shown in Fig. 4b.

These rules have been designed considering resource fairness, efficiency and solving all conflicts locally, i.e., up to the first tier of neighbors. This choice was made to reduce the need for signaling and the complexity of the underlying inter-HeNB communication protocol, as well as avoiding reconfiguration storms. The main reason being that there is no straightforward way for a HeNB to know how far it is from the edge of the network. If further communication is considered, e.g. with the second tier of neighbors, refinements are possible at the cost of increased complexity, e.g. the left- and rightmost HeNBs in Fig. 4b could become free-riders.

III. SIMULATION METHODOLOGY

A. Simulation Tool

The performance was evaluated through semi-static system level simulations. The simulator is based on basic LTE specifications [10]. It relies on series of “snapshots”. During each snapshot, path loss, shadowing and the location of devices remain constant. Fast fading is not explicitly simulated; therefore, results can be viewed as the performance averaged over a sufficiently long time period. Moreover thousands of snapshots are simulated to ensure statistical reliability.

We consider a full buffer traffic model and a 2x2 antenna configuration for all links allowing up to two code words. A simple equal resource sharing (round-robin) packet scheduling algorithm is assumed. Open-loop uplink Fractional Power Control (FPC) as standardized by 3GPP [11] for LTE is modeled as well.

For any given UE, the signal to interference and noise ratio (SINR) is calculated according to the UE’s specific parameters (interfering cells, allocation of PRBs, etc.). Error vector magnitude (EVM) modeling is present in order to account for various imperfections in the implementation of Radio Frequency (RF) components and imposes an asymptotical limit to SINR values. Look-up tables map the SINR to corresponding throughput values according to a modified Shannon’s formula from [9]. The raw spectrum efficiency is upper bounded to 10.04 bps/Hz due to modulation and coding scheme (MCS) limitations. The most important parameters are summarized in Table I.

B. Deployment Scenario

We consider a block consisting of two stripes of apartments, each stripe having 2 by 10 apartments per floor in a total of 6 floors, thus totalling 240 apartments. There is a 10m wide street between the two stripes of apartments. The area of the block is therefore 120m x 70m.

Partially owing to the full buffer assumption and in order to simulate an absolutely worst case scenario, the multi-layered resource allocation is not considered; therefore CCs are not further subdivided neither in time nor frequency. Instead, the entire bandwidth was divided into 6 equal CCs, thus permitting coalitions of cardinality up to 3, where HeNBs can be allocated 2,3,4 or 6 CCs according to the proposed rules. It is assumed that with probabilities $P = 25\%$ (dense deployment) and $P = 75\%$ (denser deployment) there is one...
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TABLE I
ASSUMPTIONS FOR SYSTEM-LEVEL SIMULATIONS

<table>
<thead>
<tr>
<th>System Model</th>
<th>Spectrum allocation</th>
<th>6 CCs of 5 MHz each</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duplexing scheme</td>
<td>TDD</td>
<td>UL: 50%</td>
</tr>
<tr>
<td>EVM</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>eNB parameters</td>
<td>TX power</td>
<td>23 dBm</td>
</tr>
<tr>
<td></td>
<td>Antenna system</td>
<td>Omni (3dBi)</td>
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<tr>
<td>UE parameters</td>
<td>Max. TX power</td>
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<tr>
<td></td>
<td>Min. TX power</td>
<td>−40 dBm</td>
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<tr>
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<td>Antenna system</td>
<td>Omni (0dBi)</td>
</tr>
<tr>
<td></td>
<td>UL</td>
<td>FPC (−60 dBm, 0.8)</td>
</tr>
</tbody>
</table>

Deployment Model [6]

| Dense Urban           | Room size           | 10m x 10m            |
|                       | Street width        | 10 m                 |
|                       | Internal walls      | 5 dB attenuation     |
|                       | External walls      | 10 dB attenuation    |

Propagation Model [6]

| Minimum coupling loss | 45 dB               |
| Shadowing std. deviation | Serving Cell | 4 dB             |
|                       | Other Cells        | 8 dB                |

Traffic Model

| User distribution     | Uniform: 1 UE/cell (Indoor) |
| Data generation       | Full buffer                |

IV. RESULTS AND DISCUSSIONS

A. Performance Analysis

All the throughput results were normalized by the maximum theoretical capacity of the system. Hence, a normalized throughput of 100% means transmission over the whole bandwidth at the maximum system spectral efficiency.

Figure 5 shows the empirical cumulative distribution function (CDF) of cell throughput, at 25% deployment ratio. Three cases are compared: universal reuse (1/1), hard reuse 1/2 and SOCCER. In a sparser deployment such as the one considered in Fig. 5, the reuse 1/2 approach becomes clearly bandwidth limited for most of the cells. This can be concluded from the nearly vertical lines. Reuse 1/1 provides a better average throughput than reuse 1/2 since the band is doubled, but that inflicts a high penalty to those cells which have an unfavorable geometry due to the uncoordinated deployment. On the contrary, the proposed method can adaptively choose the spectrum allocation outperforming both reuse patterns in terms of average cell and 5% outage throughput. One can conclude that the proposed method is very efficient in attaining a minimal quality even for the cells which have a strong interference coupling.

Note, that in our method it is acceptable to have a small loss in one link direction for the common good. This can be seen from the small CDF range in Fig. 5 where reuse 1/1 has better performance then the proposed method. We purposefully introduce symmetry, taking the lowest Incoming/Outgoing C/I value to represent the interference coupling between two cells. If there is a significant imbalance between outgoing and incoming C/I ratios, one cell loses a bit of capacity (e.g.in the DL) and the other one will gain. However, in the opposite direction (UL), the situation is reversed and in total, everybody benefits in one way or another. Therefore, the same cells which lose compared to universal reuse in one direction are the ones which gain the most in the opposite direction and, for that reason, the whole network can benefit from enhanced average capacity.

In Fig. 6 we consider a denser deployment, i.e. $P = 75\%$. On such a dense network most cells become interference limited instead of bandwidth limited. In an interference limited scenario, reuse two becomes a more interesting alternative to reuse one. In fact, in a dense deployment strong interference coupling appears more often and, hence, reuse one yields severely degraded outage performance. Our method adapts to this situation, providing similar results to reuse two in terms of 5% outage and average throughput. The peak capacity of SOCCER, at 95% of CDF, is 40% higher than reuse two in uplink and 28% in downlink.

B. Analysis of network graphs

In Section II-C, in order to limit the complexity, we suggested to limit the number of interferers to which each base station signals their intent to join coalitions. Now, we shall revisit this concept. Let us first model the network as an undirected graph, with a vertex for each HeNB and edges to represent strong bonding. Using graphs as a model, a maximal clique of size $\alpha$ represents a subset of $\alpha$ HeNBs such that every two HeNBs in the subset are connected by an edge and the

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sentative characterization of the system performance in order
(sub-)divide a resource and to be in possession of a repre-
justments. The only requirements are the ability to flexibly
autonomic communication systems with relatively simple ad-
the proposed resource sharing scheme can be adapted to other
subsets can not be extended to $\alpha + 1$ HeNBs.

The two pie charts in Fig. 7 show the relative occurrence
of maximal cliques of various sizes in the interference graph
of the simulated scenarios. Even in very dense scenarios,
maximal cliques of cardinality larger than 3 are infrequent.

SOCCER forms coalitions that closely match the maximal
clique sizes on the interference graph. This means that the
simplified method will work very efficiently on most of the
cases on the investigated scenario. Note also that the method
is not necessarily inefficient if there are cliques larger than
size 3. When a multi-layered resource allocation is considered
as shown in Fig. 1, then the conflicts of cliques of size 4
or larger can be solved on the higher level. Considering the
distributions of clique size in a typical deployment scenario
(Figs. 7a and 7b), the traffic variability and the extensibility
to multi-layered resource allocation we suggest to apply the
simplifying assumption to practical cases.

C. Practical considerations

Potential applications beyond those described are numerous;
the proposed resource sharing scheme can be adapted to other
autonomic communication systems with relatively simple ad-
justments. The only requirements are the ability to flexibly
(sub-)divide a resource and to be in possession of a represen-
tative characterization of the system performance in order
to estimate the value of coalitions. For simplicity, we have
demonstrated an LTE-Advanced system whose bandwidth was
divided into 6 CCs to accommodate coalitions of up to three
devices sharing the same resource. However, if 6 CCs are
not readily available, the framework shown in Fig. 1 can be
directly utilized, if 6 orthogonal resources are created via e.g.
Time-Division Multiple Access (TDMA). In this case, TDMA
could be employed in order not to sever an LTE-Advanced
CC into smaller chunks. In these circumstances, cells would
be entitled to one autonomously selected base/anchor carrier,
which is “untouchable”; i.e. it is always active, indivisible
and may only be re-used by cells without strong bonding,
while sharing supplementary or secondary CCs according to
the formation rules.

V. CONCLUSION

This contribution introduced a new mechanism, which en-
ables femtocells to self-adapt and autonomously share re-
ources aiming at efficient network operation. The proposed
method presents three highly desirable virtues; it is simple,
practical and delivers very attractive performance results.
Based on the evaluation of the mutual interference coupling
between pairs of HeNBs, it leads to sensible cooperation via
multilateral agreements following a simple set of rules, which
by construction preclude disruptive reconfiguration avalanches.
The algorithm has been extensively tested by means of com-
puter simulations in dense urban deployment scenarios within
an LTE-Advanced framework. The obtained results prove the
proposed method is able to outperform traditional pre-planned
frequency reuse patterns both in terms of average and 5%
outage throughput per cell. Moreover, when modeling the
network as a graph, results also demonstrated that maximal
cliques larger than 3 are rather infrequent even in extremely
dense networks operating at full load; this result illuminated
an important aspect of the problem structure and justified the
limit imposed by design on the maximal coalition size.

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