Self Organized Physical Cell ID Assignment in Multi-operator Heterogeneous Networks

Furqan Ahmed and Olav Tirkkonen
Dept. of Communications and Networking, Aalto University
P.O. Box 13000, FI-00076 Aalto, Finland

Abstract—**We discuss Physical Cell ID (PCI) assignment for densely deployed heterogeneous networks (HetNets), in a multioperator spectrum sharing scenario. The aim is to achieve PCI assignment that is conflict-free and confusion-free, jointly for multiple operators, in a self-organized way. A graph coloring formulation is used to model the problem where the PCIs represent the colors used to color the interference graph. The graph is created using the interference couplings determined by handover measurements of the user equipments served by the HetNet. The PCI assignment algorithms considered are based on local search methods used in conjunction with the focused search principle, which allows PCI reconfigurations only to the cells with unsatisfied constraints related to conflicts and confusions. The algorithms considered are fully distributed and do not involve message-passing between the operators. Each cell decides its PCI by observing the PCIs of its neighbors which include its own network cells as well as the cells that belong to the other operators but share the same spectrum. Simulations results show that the proposed algorithms have good convergence properties and are effective for self-organized PCI assignment in dense multioperator networks with shared spectrum.**

I. INTRODUCTION

Self-organization is a cornerstone in the success of contemporary cellular networks such as Long Term Evolution (LTE)/LTE-Advanced (LTE-A), especially when dense deployments of small cell networks are considered. In the LTE/LTE-A systems standardized by the 3rd Generation Partnership Project (3GPP), the automatic mechanisms for self-optimization, self-configuration, and self-healing are considered as use-cases of Self Organizing Networks (SON) [1]. Many functionalities and use-cases related to self-organization are expected to be evolved for future cellular networks such as 5G.

The Physical Cell ID (PCI) assignment problem is considered as one of the most important SON use-case for LTE/LTE-A, and has been discussed extensively from both technical and standardization perspectives [2]. The PCI is a physical layer signature for distinguishing signals from different Base Stations (BSs) in LTE/LTE-A networks. It is based on synchronization signals and plays a key role in several important procedures such as handovers, configuration of physical layer measurements for SON related functionalities, configuration of uplink and downlink reference signals, and Automatic Neighbor Relations. The total number of PCIs in LTE/LTE-Advanced is 504, which consists of 168 PCI groups, each comprising of 3 unique IDs. Thus, reuse is inevitable especially in dense heterogeneous network (HetNet) deployments envisaged for meeting the increasing demands of high capacity and better coverage. Automated PCI assignment aimed at achieving conflict-freeness for unique cell identification and confusion-freeness for effective handover performance is therefore regarded as an important issue [1]. This concept of PCI is of special interest from the perspective of future networks, as it is a highly efficient way of identifying cells regionally. It takes 5ms to read a reference signal to determine the ID and the design is inherently robust against interference. Due to its efficiency, we believe that a physical layer ID mechanism meant for identifying cells is important for future networks, whether they are based on LTE evolution, or on a clean slate 5G design. A limited ID space is essential for effective cell search. The importance of the PCI assignment problem is further underscored by the fact that ultra dense HetNet deployment scenarios comprising of multiple tiers of cells are currently being considered for enabling high capacity in 5G networks. In such networks, self-organized assignment of cell IDs will be of paramount importance for ensuring seamless handovers and efficient operation [3].

In the context of conflict-free and confusion-free PCI-configuration, [4] discusses the mapping of the PCI assignment problem to a graph coloring problem along with a centralized coloring algorithm for PCI assignment. Distributed approaches for PCI assignment have been discussed in [3], [5]–[7]. In [5], potential conflicts arising from distributed PCI assignment are solved by reserving ID-space for newly switched-on BSs. The newly switched-on BSs use the assigned ID for a limited amount of time during which the BSs negotiates with neighbors to discover PCIs that are conflict-free and confusion-free. In [6], different distributed graph coloring algorithms are used to assign the PCI, without partitioning the ID-space. These include distributed greedy local search algorithms and constraint satisfaction algorithms. Moreover, the methods proposed in [3] and [7] hinge upon explicit cooperation through signaling between the cells.

In this paper, we consider dense HetNet deployments in a multi-operator spectrum sharing scenario where operators share the spectrum in the small cell layer which comprises of pico-cells, thereby complicating PCI assignment problem. We assume that PCI is a resource for a given spectrum, the full range of PCIs is available for the pico-cells of all operators, and the operators are not interested in active cooperation via message-passing. Accordingly, cells belonging to different operators cannot exchange information over backhaul and just rely on handover measurements for inter-operator PCI assignments—cooperative PCI assignment schemes are out of question. This setting is relevant to future networks which will comprise of multilayer, multi-operator architectures with different spectrum sharing models [8]. Unlike [3], [7], [9] that consider cooperation among cells in a single operator network, our focus is on fully distributed algorithms that do not involve cooperation between cells belonging to different operators. When different operators share the same spectrum, PCI conflicts and confusions need to be resolved. We propose PCI assignment algorithms based on a *focused search* metaheuristic, which has been used in many algorithms designed to solve different constraint satisfaction problems [10], [11]. It proves to be effective for PCI assignment as well, and has properties which make it inherently suitable for enabling distributed self-organization in future networks.

The rest of the paper is organized as follows: Section II describes the system model and formulation of graph coloring problem. Section III introduces the graph coloring concepts and discusses in detail the proposed algorithms for PCI assignment. Section IV shows simulation results for a densely deployed HetNet, followed by a discussion on the performance of the proposed approaches. We conclude in Section V.

II. SYSTEM MODEL

We consider graph coloring formulation of the PCI assignment problem for a HetNet comprising of multiple operators with an overlapping coverage area and common spectrum in the small cell layer. This formulation enables using various local search metaheuristics and constraint satisfaction algorithms. Each operator has both a macro-layer and a small cell layer. The macro-layer spectrum allocation among operators is orthogonal. The small cell layers use a dedicated spectrum, with inter-operator spectrum sharing enabled. It is assumed that the PCI resource is shared by the small cell networks belonging to different operators. These PCIs are used in handover signaling between the small cell and macro-cell layers. Accordingly, it is important for an operator network to know, which neighbors belong to the own operator network. Conflict-freeness and confusion-freeness in the PCI space should extend across all small cell networks sharing the spectrum.

A. Interference Graphs

We describe the HetNet by an interference graph where nodes correspond to the cells, and edges are binary valued interference couplings. An edge couples two cells sharing the same spectrum that should have different PCI to avoid conflicts and confusions. Both cells within a network and in different networks may be coupled by edges. Interferers are identified using handover measurements, where each User Equipment (UE) selects its serving BS on the basis of received signal power, and reports interfering BSs to its serving BS. Note that both other- and own-network interferer information is gathered by the BSs. A UE can synchronize only to BSs from which the received SINR exceeds the threshold H_{sync}, and BSs with received SINR greater than H_{sync} are reported as interferers. The synchronization threshold effectively models the measurement and reporting limitations of the UEs. Consider a BS V, which has own network interferers X and other operator interferers Y. To handle the conflict constraints, it adds directional edges towards itself from both X and Y. For handling confusion constraints it requests its own network interferers X to add an incoming edge, between X and itself, and from Y to X. Thus, information exchange via message-passing is within the own network only.

An implication of limited interaction among the cells belonging to different operators is that the resulting interference graph is not necessarily symmetric, which complicates the coloring problem and distinguishes the problem addressed here from the single-network case addressed in the literature. This is illustrated in the interference graph shown in Fig. 1 which delineates asymmetric conflicts and confusions that arise when nodes belonging to the red and blue operators interact to create an interference graph. Here, the arrow points from the interferers to a given node which is an interference victim. In Fig. 1(a) node V belonging to operator blue adds directed edges from its own operator neighbors $X1$, $X2$ as well as other-operator neighbors $Y1$ and $Y2$. These directed edges correspond to the conflict-freeness constraints. Then as shown in Fig. 1(b), it request its own operator neighbors to add confusion-freeness constraints. Below, the terms “PCI conflict” and “PCI confusion” are collectively called “conflicts” in the discussion pertaining to the directed conflict graph representation of the problem.

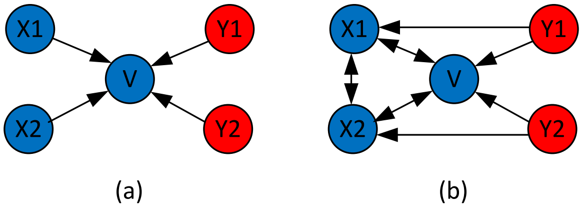

Fig. 1. Asymmetric conflicts and confusions in a multi-operator graph.

B. Distributed Graph Coloring

Distributed graph coloring has mostly been investigated for cases in which the number of colors are $\Delta + 1$ or $O(\Delta)$, where Δ is the largest number of neighbors of any node [12]. If the number of colors is smaller than Δ, generic constraint satisfaction algorithms [13] can be used. In [6] we discussed these algorithms in detail for self-organized primary component carrier selection and PCI assignment. The algorithms are based on local search and are classified by two characteristics. The first classification is based on type on interference pricing which represents the interference coupling between the nodes. A real-valued interference pricing may be used when we consider real-valued interference coupling between the nodes. On the other hand, a binary price is used when the decisions are based just on the number of binary conflicts and not on their strength. The second classification is done according to the number of attempts made by a node to improve its interference situation by switching the color, e.g., single-try and multiple-try algorithms. In the single-try algorithms, a node randomly selects a color and makes a decision to use it based on some criterion, whereas the multiple-try entails steepest descent in which all colors are tried and the best one is selected.

For the current multi-operator PCI assignment problem, we consider binary couplings only and without pricing exchange among the cells. This is due to the assumption that operators do not exchange information and the cells can only passively observe the neighboring PCIs. Thus, the adjacency matrix of the interference graph is not fully symmetric which makes the problem more challenging.

III. ALGORITHMS

We discuss distributed algorithms based on local search mechanism, which is a well known method used for solving combinatorial optimization problems. It involves searching for the optimal solution in the solution space by making local changes to the current solution in a systematic manner.

A. Local Search: Plateau and Downhill Moves

In the distributed local search methods, the agents explore the solution space by changing the configuration to move from one solution to another in the solution space. The local move from one solution to another is enabled via small perturbations to the existing solution. These small perturbations lead to transition to the neighboring states, whereas the neighboring states in the solution space are two states that are connected by a local move. The local move which reduces the cost function (or increases the utility), is often known as a *downhill* move. For example, in a distributed graph coloring problem, the local move by a node constitutes a change in the color, and it can be classified as a downhill move if it reduces the number of conflicts the node has with its neighbors. Another characteristic of solution space in conflict graph coloring problems is the existence of plateaus, i.e., neighboring states with the same number of conflicts. Thus, a local move in which the number of conflicts remain the same is known as a *plateau* move. The plateau moves are essential for avoiding entrapment in the local optima and increase the possibility of finding a global optimum. The key idea of local search algorithms is to make use of downhill and plateau moves to find the globally optimal solution. For the PCI selection problem, a local move in the solution space is the change of PCI by one cell. In the algorithms we discuss here, this move will either be downhill move or a plateau move. Thus, the solution space is searched for a colored state corresponding to conflict-free and confusion-free PCI assignment by a sequence of local moves taken by the cells.

B. Focused Search Algorithms

An important consideration for PCI assignment problem is to keep the local moves to a minimum as switching PCI essentially means rebooting the cell. This can be achieved by allowing the local moves only to the cells that are in conflict. The principle of allowing the local moves only to the unsatisfied nodes in combinatorial optimization problems is known as *focused search* [10], [11]. Moreover, the underlying graph for the spectrum sharing PCI assignment problem is not symmetric. Thus, the random plateau moves by nodes with all constraints satisfied may not be plateau moves for the whole network, as constraints of other-operator nodes that a node is not aware of, may be violated. We therefore consider focused plateau moves in conjunction with stochastic local search to design an iterative algorithm for the PCI assignment problem. In each iteration, a given cell v using PCI c, if in conflict, randomly selects a PCI $c' \in \mathcal{C} \backslash c$, where $\mathcal{C}$ is the full range of PCIs. It evaluates the number of conflicts $\mathcal{F}(c')$ resulting from PCI c'. It starts using the selected PCI if doing so either reduces the number of conflicts, or keeps them unchanged $\mathcal{F}(c') \leq \mathcal{F}(c)$. The procedure is repeated in every iteration by all the cells that are in conflict with their neighbors. The algorithm is summarized in Algorithm 1 as stochastic local search with focused plateau moves (SLS-FP) algorithm. Thus, the plateau moves are focused only on the cells that see one or more conflicts. Note that this also helps to limit the spread of conflicts to already colored parts of the graph, which is important because of practical reasons. In addition, we consider an enhancement to SLS-FP, such that in the first step a cell tries all the PCIs and selects the best one, rather than selecting one randomly. This variant is given as steepest descent local search with focused plateau moves (SDLS-FP) in Algorithm 2. The underlying principle here is that a cell selects the best PCI (or moves in steepest direction) among all possible alternatives in the first step. This is followed by the downhill or plateau move. Clearly, the steepest descent principle for selecting a PCI leads to a higher computational complexity as compared to the stochastic selection of PCI, and is expected to perform better than SLS-FP. However, both algorithms are simple to implement and perform well in practice as discussed in the following section.

Algorithm 1 SLS-FP

```
Cell $v$ using PCI $c$ selects a PCI $c' \in \mathcal{C} \backslash c$ and computes:
    $\Delta = \mathcal{F}(c') - \mathcal{F}(c)$.
if ($\mathcal{F}(c) > 0$  and  $\Delta \leq 0$) then
    $c \leftarrow c'$
else
    $c \leftarrow c$
end if
```

Algorithm 2 SDLS-FP

```
Cell $v$ using PCI $c$ selects a PCI $c' \in \mathcal{C}$ such that:
    $c' = \arg\min_{c \in \mathcal{C}} \mathcal{F}(c)$ and computes: $\Delta = \mathcal{F}(c') - \mathcal{F}(c)$.
if ($\mathcal{F}(c) > 0$  and  $\Delta \leq 0$) then
    $c \leftarrow c'$
else
    $c \leftarrow c$
end if
```

IV. SIMULATION RESULTS

In order to analyze the performance of proposed algorithms, we consider a multi-operator HetNet with a macro-layer and a pico-layer. The performance metrics analyzed here are the probability of convergence to a fully colored state, the corresponding number of iterations required for convergence, and the number of PCI reconfigurations in the network.

A. Scenario

A HetNet comprising of two operators with overlapping coverage area and shared spectrum in the pico-layer is considered. The macro-layer of each operator entails a 10×10 grid of hexagonal cells, were the grids of the operators are overlapping but not aligned. In each hexagonal cell 10 small cells are dropped randomly, and the number of users per cell is also fixed to 10. Thus total number of BSs in the whole network is 2200, with 1100 belonging to each operator. Each user is associated with either operator 1 or operator 2, both

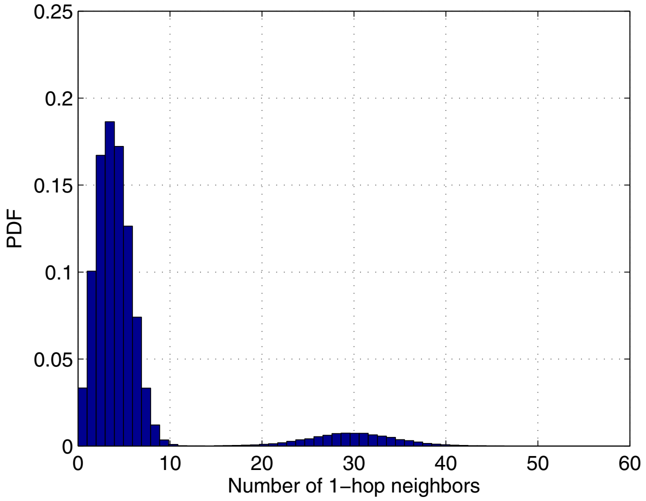

Fig. 2. Distribution of 1-Hop neighbors in the interference graph.

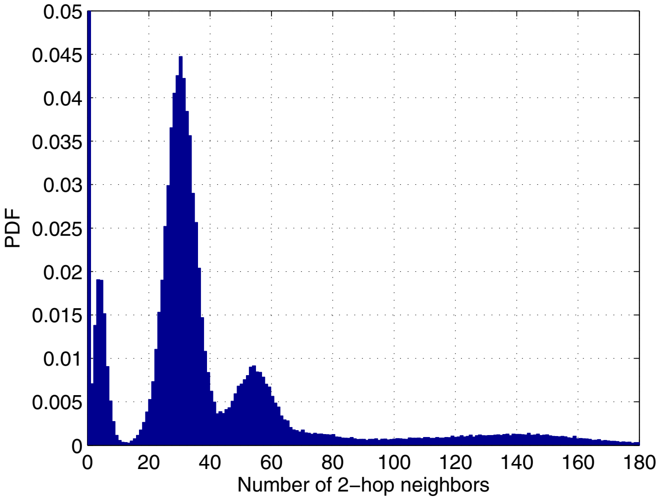

Fig. 3. Distribution of 2-Hop neighbors in the interference graph.

having same probability. The best BS of the own operator network (in terms of received signal power) is chosen as the serving BS by each user. The potential interferers are the ones to which a user can synchronize under the synchronization threshold $H_{sync} = -7$ dB. Moreover, shadow fading is taken into account and the detailed simulation parameters are given in Table I. The path loss for an outdoor-to-indoor pico-cell is calculated according to [14]

$$PL = 56\log_{10}(d) + 175 \tag{1}$$

where d is the distance between pico BS and UE and f_c is the carrier frequency. Similarly, the path loss for an outdoor-to-indoor macro-cell is calculated as

$$PL = 37.6\log_{10}(d) + 148.1 + 20\log_{10}(f_c/2) \tag{2}$$

Based on the parameters given in Table I, different random instances of the network can be created to gather the statistics for performance analysis. For each network instance, the interference graph is constructed on the basis of handover measurements, using the procedure explain earlier. The statistics of 1-hop and the 2-hop neighbors in the interference graph are shown in Fig. 2 and Fig. 3 respectively, for 100 randomly generated network instances. It can be observed that disparity in the powers of macro-BSs and pico-BSs give rise to non-uniformity in the neighbor relations of the nodes in interference graph.This translates to multiple peaks in the distributions of 1-hop and 2-hop neighbors. Recall that for PCI assignment, both 1-hop and 2-hop neighbors must be avoided while selecting a PCI for a given cell, and the interference graph takes into account these constraints. The performance of the proposed algorithms towards achieving this objective is discussed in the next section.

TABLE I. SIMULATION PARAMETERS

Number of macro-BSs	100 per operator
Number of pico-BSs	1000 per operator
Number of MSs	10 per cell
Bandwidth	20 [MHz]
Bandwidth Efficiency	0.9
Transmit Power macro-BS [dBm]	43
Transmit Power pico-BS [dBm]	27
Noise figure [dB]	9
Thermal noise [dBm/Hz]	-174
Shadow fading correlation	0.5
Shadow fading standard deviation [dB]	8
Carrier frequency (f_c)	3.6 [GHz]

B. *Numerical Results*

To determine the minimum number of PCIs required for conflict-freeness and confusion-freeness, a random network instance is created and both SLS-FP and SDLS-FP algorithms are run till convergence to a colored state, for a range of PCIs. The maximum number of iterations for both algorithms is fixed to 1000, and the results are averaged over 100 network instances. The probability of convergence to a completely colored state versus the number of PCIs is given in Fig.4. It can be seen that both algorithms can successfully reach the fully colored state with a reasonable number of PCIs. The convergence with probability one is possible with only 120 PCIs, in the fairly dense HetNet scenario considered here. Moreover, SLS-FP can achieve the same probability of convergence as SDLS-FP with smaller computational burden. The complementary plots illustrating the iterations required for convergence are given in Fig.5. The SDLS-FP requires less iterations compared to SLS-FP due to the steepest descent principle. This smaller number of iterations also translates into reduced number of reboots or reconfigurations per cell, which is shown in Fig.6. Furthermore, it is important to note resulting conflict-free and confusion-free assignment of PCIs is achieved in a fully distributed way. In execution phase, the only message-passing is related to informing own-network neighbors about colors used by their 2-hop neighbors.

V. CONCLUSIONS

In this paper, we proposed distributed self-organizing algorithms for PCI assignment in multi-operator HetNets with shared spectrum in the small cell layer. The algorithms are based on the focused search principle designed to search the solution space efficiently while minimizing the number of

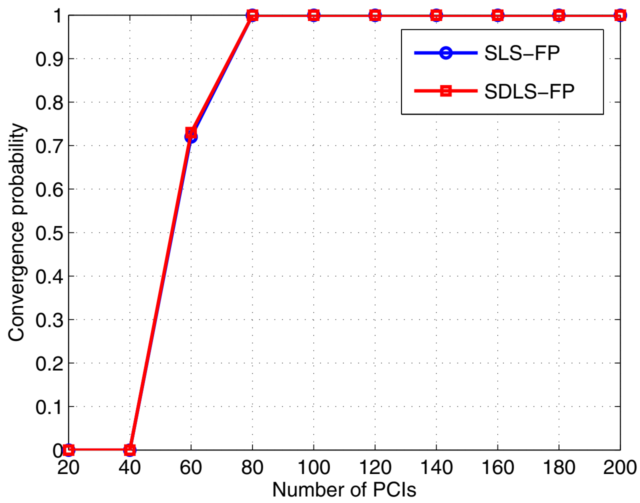

Fig. 4. Convergence of PCI assignment algorithms vs number of PCIs.

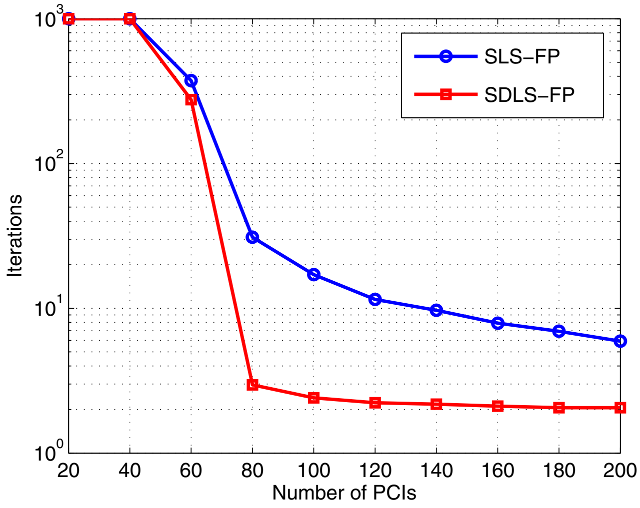

Fig. 5. Iterations required for convergence of PCI assignment algorithms.

reconfigurations in the network. In a HetNet, a macro-cell may have a large number of neighboring small cells, and an even larger number of 2-hop neighbors. In a multi-operator setting, where the nodes do not have complete information of all the consequences of their actions, the resulting problem is challenging. However, simulation results show that the proposed algorithms can enable conflict- and confusion-freeness in multi-operator networks without the need of any explicit coordination such as message-passing, between the other-operator cells.

ACKNOWLEDGMENT

We thank Konstantinos Koufos for the discussions on subject matter. This work was supported by the European Commission in the framework of FP7 project ITC-317669 METIS.

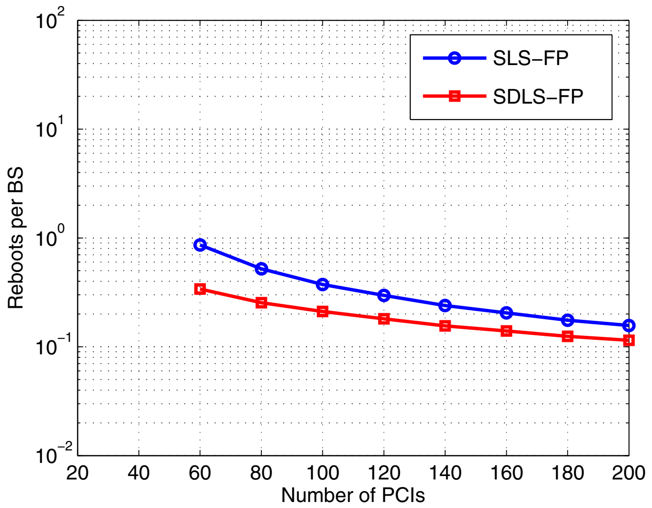

Fig. 6. Required number of reboots per BS for PCI assignment.

REFERENCES

[1] 3GPP, "Evolved universal terrestrial radio access; self-configuring and self-optimizing network use cases and solutions (Release 8)," Tech. Rep. TS 36.902 v0.0.1, 2008.

[2] S. Hämäläinen, H. Sanneck, and C. Sartori, *LTE Self-Organising Networks (SON): Network Management Automation for Operational Efficiency*. Wiley, 2011.

[3] A. Diab and A. Mitschele-Thiel, "Development of distributed and self-organized Physical Cell Identity assignment schemes for LTE-Advanced systems," in *Proc. ACM Workshop on Perf. Monit. Meas. Het. Wirel. Wired Networks*, Nov 2013, pp. 83–90.

[4] T. Bandh, G. Carle, and H. Sanneck, "Graph coloring based Physical-Cell-ID assignment for LTE networks," in *Proc. IEEE Internat. Wireless Commun. & Mob. Comp. Conf.*, Jun. 2009, pp. 116–120.

[5] Nokia Siemens Networks and Nokia, "SON use case: Cell Phy_ID automated configuration," 3GPP, Tech. Rep. R3-080376, 2008.

[6] F. Ahmed, O. Tirkkonen, M. Peltomäki, J.-M. Koljonen, C.-H. Yu, and M. Alava, "Distributed graph coloring for self-organization in LTE networks," *Journal of Electrical and Computer Engineering*, pp. 1–10, 2010.

[7] Y. Liu, W. Li, H. Zhang, and L. Yu, "Distributed PCI Assignment in LTE Based on Consultation Mechanism," in *Proc. Int. Conf. on Wireless Commun. Networking and Mobile Computing*, Sept 2010, pp. 1–4.

[8] T. Irnich, J. Kronander, Y. Selen, and G. Li, "Spectrum sharing scenarios and resulting technical requirements for 5G systems," in *Proc. IEEE PIMRC Workshops*, Sept 2013, pp. 127–132.

[9] M. Amirijoo, P. Frenger, F. Gunnarsson, H. Kallin, J. Moe, and K. Zetterberg, "Neighbor Cell Relation List and Physical Cell Identity Self-Organization in LTE," in *Proc. IEEE ICC Workshops*, May 2008, pp. 37–41.

[10] S. Seitz, M. Alava, and P. Orponen, "Focused local search for random 3-satisfiability," *J. Stat. Mech*, 2005.

[11] M. Alava, J. Ardelius, E. Aurell, P. Kaski, S. Krishnamurthy, and P. Orponen, "Circumspect descent prevails in solving random constraint satisfaction problems," *Proceedings of the National Academy of Sciences (USA)*, vol. 105, no. 40, pp. 15 253–15 257, October 2008.

[12] F. Kuhn and R. Wattenhofer, "On the complexity of distributed graph coloring," in *Proc. ACM Symp. Princip. of Distr. Comp.*, Jul 2006.

[13] M. Yokoo and K. Hirayama, "Algorithms for distributed constraint satisfaction: a review," *Auton. Agents and Multi-Agent systems*, vol. 3, no. 2, pp. 185–270, 2000.

[14] 3GPP, "Physical layer aspects for evolved universal terrestrial radio access (UTRA)(Release 7)," Tech. Rep. TR 25.814, 2009, available: http://www.3gpp.org.