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Voice-Centric LTE Femtocells and Improper Graph Colorings

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***Abstract*—This paper addresses carrier-based inter-cell interference coordination (CB-ICIC) among LTE femtocells operating on a single carrier. CB-ICIC is in many ways linked to the widely investigated dynamic channel assignment problem, which is often studied in the context of graph coloring. The investigation revolves around the sensible definition of the underlying graph, i.e. the network model, rather than focusing on the coloring algorithms and their properties. Ultimately, we posit that improper online graph-coloring suffices and is actually preferable. In short, settling for less-than-optimal configurations avoids uncontrolled service interruptions. Such disruptions tend to raise understandable concerns when it comes to fully autonomous selection of operational CCs. Our results dispel such concerns by showing that conservative methods can achieve most of the benefits of unrestricted off-line coloring algorithms with a very modest number (2-3) of CCs to choose from.**

***Index Terms*—Femtocells, LTE, Spectrum Sharing, Graph Coloring, Self-organizing.**

I. Introduction

In recent years, mobile traffic has witnessed astronomical annual growth rates, a trend which is not only expected to continue but also to be intensified. Analysts predict that mobile traffic is expected to increase 1000 times in the period between 2010 and 2020 [1]. Meeting the foreseen traffic demand in a cost-effective manner is a daunting challenge. The designers of wireless systems cannot create more bandwidth by endlessly adding new physical resources. Complicating matters further is the fact that current cellular systems come very close to the fundamental limits imposed by the laws of physics in terms of *spectral efficiency per link* (bit/s/Hz).

On the other hand, the *spectral efficiency per unit area* can be increased almost arbitrarily by taking the cellular concept to the extreme. In this respect, femtocells, also known as home-eNBs (HeNBs) are a major step towards network densification. Similar to WiFi access points, they are miniature user-deployed and controlled base stations, compact enough to find a place in our homes and offices. Femtocells rely on existing third party IP-based backhaul and offer significantly higher capacity per area when compared to traditional macro cells. However, the potential benefits offered by femtocells are not without new challenges in terms of interference management. Due to the expected large number of user-deployed cells, centralized network planning becomes unpractical and new scalable alternatives must be sought.

This contribution addresses interference and spectrum management techniques in the ambit of LTE networks. More precisely, carrier-based inter-cell interference coordination (CB-ICIC) among femtocells operating with a single Component Carrier (CC) such as, but not limited to, voice-centric femtocells. Investigating CB-ICIC schemes is relevant because carrier-based solutions have the intrinsic advantage of being fully compatible with legacy User Equipments (UEs). Moreover, CB-ICIC solutions offer protection to both data and control channels. The protection offered to control channels is specially relevant in the presence of cells operating in closed subscribed group (CSG) configuration. None of the existing mechanisms were designed to shield these channels from intra-tier (femto-to-femto) inter-cell interference, which can be disastrous[1] in case of unfavorable network topology. One should never forget that improved data Signal to Interference-plus-Noise Ratio (SINR) is useless if UEs cannot decode control channels.

CB-ICIC is in many ways linked to the widely investigated dynamic channel assignment problem [2]–[4]. Mathematically, channel assignment is a combinatorial optimization task which can be mapped into a conflict graph vertex coloring problem and is therefore NP-hard. Several centralized and distributed vertex coloring algorithms exist and many contributions in the literature have analyzed the multi-cell spectrum allocation problem in light of graph coloring [5], [6]. Notwithstanding, much of the previous work focused on finding *proper* colorings, studying the convergence characteristics, the computational complexity and optimality of the algorithms.

Although this paper also looks into online distributed graph coloring, the investigation revolves around the sensible definition of the underlying graph, i.e. the network model, rather than focusing on the algorithms. Ultimately, we posit that improper (weak) online graph-coloring suffices and is actually preferable. Simply put, algorithms striving for strict optimality (proper coloring) may lead to uncontrolled/unpredictable reconfiguration storms because user-controlled femtocells can (re-)appear anywhere and at anytime. Due to the potential uncontrolled service interruptions, operators tend to be understandably cautious when it comes to autonomous selection of operational CCs. Our results dispel such concerns by showing that conservative methods can achieve most of the benefits of unrestricted off-line coloring algorithms with a very modest number (2-3) of CCs to choose from.

[1]In time (frame) synchronized LTE networks, DL control channels are always transmitted at the same time and frequency, hence unlike data channels collision is guaranteed.

The rest of this paper is organized as follows: Section II covers some basic concepts from graph theory. Section III describes our system model, formalizes the problem and, introduces the considered strategies to map the network topology into a graph model. Section IV outlines the simulation assumptions, presents, and discusses the system level simulation results obtained. Finally, Section V summarizes the main findings and concludes the paper.

II. Graph Theoretic Preliminaries

This section formalizes a few concepts that will be used throughout the paper. Readers familiar with the basic definitions from graph theory may proceed to the next section. Those interested in more details are referred to [7].

A. Basic Definitions

- An undirected graph G is a mathematical structure consisting of an ordered pair $G = (V, E)$, where V is the finite set of elements called *vertices*, while E is a finite unordered pairs of vertices called *edges*. Two vertices $u, v \in V$ are called *adjacent* if $\{u, v\} \in E$. In other words, two vertices are adjacent if there is a line, the edge, connecting them.
- The degree $deg(v)$ of a vertex $v \in V$ is the number of edges incident to vertex v, while the degree of a graph, denoted by $\Delta(G)$, is the maximum degree of a vertex in graph G.
- A clique V' is a subset of V, such that for every two vertices in V', there exists an edge connecting the two. A clique V' is called *maximal clique* if it cannot be extended by including one more adjacent vertex, that is, there is no V'' such that $V' \subseteq V''$. The clique number, $\omega(G)$, of a graph G is the cardinality of the largest maximal clique.
- A *proper* vertex coloring of an undirected graph G is a function $c : V \rightarrow \mathbb{N}$ such that $c(u) = c(v) \Leftrightarrow \{u, v\} \ni E$. Thus, the coloring function c assigns a color, represented here by a natural number, which is never the same for adjacent vertices.
- For any $k \in \mathbb{N}$, a vertex k-coloring is a coloring that uses exactly k different colors. The chromatic number of a graph G, denoted $\chi(G)$ is the minimum number of different colors required for a proper vertex-coloring of the graph G.

B. Mapping the Network into a Graph

In this work, the local area cellular network is mapped into a conflict graph $G = (V, E)$ where the node set, V, denotes HeNBs and the edge set, E, represents the possibility of severe co-channel interference in case of simultaneous transmissions by adjacent femtocells. When it comes to the application of graph theory to solve channel assignments problems, a very frequent approach is to resort to restricted classes of graphs, such as trees and planar graphs, for which solutions can be found in polynomial time. This pragmatic approach has been rightfully criticized in [8], because it is tailoring the problem to an existing solution rather than the opposite.

Due to the uncoordinated nature of femtocell deployments, no restrictions are imposed and arbitrary graphs are used to represent the possible network topologies. The disadvantage of arbitrary graphs is the absence of general results for the lower and upper bounds of the chromatic number $\chi(G)$, i.e. the minimal number of colors needed to attain a proper coloring. However, it can be stated that $\omega(G) \leq \chi(G) \leq \Delta(G) + 1$. That is, every graph can be properly colored with one more color than the maximum vertex degree and no less than the maximum number of vertices in a maximum clique in G.

III. System Model

A. Problem Formulation and Related Work

Let a local area network be defined as a set of N femtocells, denoted by $\mathcal{N} = \{1, \ldots, N\}$ operating in a licensed band of $\mathcal{B}$ MHz. The spectrum is divided into a set $\mathcal{C}$ of CCs of cardinality $|\mathcal{C}| = C$. Without loss of generality, let us assume that $BW(c) = \mathcal{B}/C \ \forall \ c \in \mathcal{C}$ and that all CCs experience approximately the same propagation conditions.

The problem at hand is the (re-)selection – given the topology of the network – of a suitable operational carrier aiming at reducing the interference from (and possibly to) other nodes. Ideally, two femtocells should not employ the same CC if they interfere with each others transmission. Defining the interference relation plays a paramount role in the rest of this paper, which is intimately related to previous work found in [6], [9]–[11].

Solving the problem in a fully distributed manner has the advantage of being inherently scalable. The disadvantage is that distributed mechanisms rely on *local* and typically incomplete information. Here, local means that each HeNB is directly connected to (is aware of) at most some fixed number of neighboring HeNBs that is independent of the size of the network. Moreover, when cells have no specific reasons to favor one particular CC rather than others, the autonomous channel selection procedure is equivalent to a distributed version of the vertex coloring problem. In this respect, the noteworthy work in [6] investigated the selection of a single operational carrier and analyzed the characteristics of the different classes of graph coloring algorithms. The authors showed that distributed selection of *conflict-free* channels is guaranteed to converge with $5 - 7$ or more CCs.

Perhaps, more critical to the message of this paper is that results in [6], [11] indicate that the number of HeNB reboots (channel reselections/per successfully added neighbor) is relatively high in the distributed case. This puts network stability on the line because the algorithms strive for strict optimality. Most if not all these reconfigurations can be avoided if the multiple autonomous agents exchange optimality for the sake of stability. In the following three criteria to define the interference relation, i.e. the edges, are examined.

B. Random Criterion

There is no simpler distributed alternative to allow each HeNB to select one arbitrary CC out of the C possible options. Strictly speaking, a graph theoretic framework is not

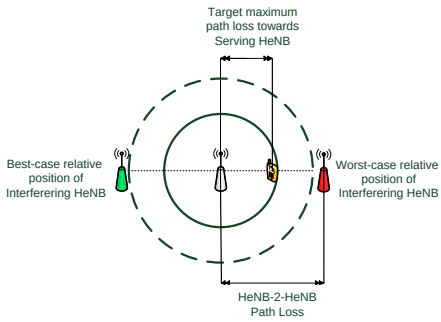


Fig. 1. An illustration of the simple model assumed in the NLM criterion. The worst-case entails that the position of the neighboring HeNB is the one leading to the strongest interference possible for a given measured HeNB-toHeNB path loss.

required to explain the outcome of a random CC selection. Nevertheless, the random criterion is included here in order to make the performance comparison more comprehensive. The process in this case is reversed: coloring takes place first and it eventually defines the graph G: Given a set V of HeNBs, the set of edges E can be understood as the outcome of a proper $C-$coloring process, where $c(u) \neq c(v) \Leftrightarrow \{u, v\} \in E$. Clearly, the resulting graph is completely arbitrary and bears no relevance to the actual structure of the network. The graph G contains no exploitable information about the interference coupling among the femtocells.

C. NLM Worst-Case Criterion

The second criterion, denoted as Network Listening Mode (NLM) Worst-Case, defines the edges without UE assistance. Simply put, the characterization is entirely based on transmitter-side information. The idea relies on HeNBs acting as a pseudo-UEs for some time after being powered up. Each HeNB scans the air interface searching for downlink (DL) pilot signals from other femtocells in order to estimate the HeNB-to-HeNB path losses.

Then, due to practical limitations of the system, it is assumed that below a certain SINR threshold, SINR_{min}, UEs are not able to decode the control channel information. For LTE, a reasonable value would be -7 dB [6]. Bearing in mind that there is no straightforward way for a HeNB to know the position of an neighboring HeNB relative to its served UE(s), the pairwise interference characterization assumes a worst-case oversimplified scenario. That is, given the HeNB-to-HeNB path loss, it is assumed that the UE is closest (in terms of path loss, not necessarily geometry) to the interfering femtocell. This is illustrated in Fig.1.

Therefore, assuming equal transmit powers and neglecting the potentially different shadow fading fluctuations between the UE and both HeNBs involved, a coarse lower bound for the SINR experienced by any UE at the edge of the desired coverage zone is: $\text{SINR} = \Lambda_{u,v} - 2L_{\text{Tgt}}$, where $\Lambda_{u,v}$ corresponds to the measured HeNB-to-HeNB path loss, and L_{Tgt} is a target path loss corresponding a desired level of coverage. In this paper, $L_{\text{Tgt}} = 80$ dB. Thus, an edge will exist between two vertices, $\{u, v\} \in E$, whenever $\Lambda_{u,v} < \text{SINR}_{min} + 2L_{\text{Tgt}}$. Based on this a conflict graph is built locally and the coloring (CC selection) takes place. As opposed to the random selection, this approach clearly exploits information about the density and topology of the network.

D. Strong-Bonding Criterion

The third criterion is based on the *strong-bonding* definition introduced by the Self-Organizing Coalitions for Conflict Evaluation and Resolution (SOCCER) algorithm presented in [10]. In simple terms, the presence of a strong bonding between two HeNBs implies that the usage of the same CC (color) is highly detrimental. In short, this approach defines the edges of the graph using receiver-side information collected by UEs in aggressor as well as victim cells. Mathematically, a strong bonding occurs whenever:

$$\frac{C(\text{SNR}_u) + C(\text{SNR}_v)}{2} \geq C(\text{DL}_{\{u\}\rightarrow\{v\}}) + C(\text{DL}_{\{u\}\leftarrow\{v\}}) \tag{1}$$

Essentially, (1) says that the SINR gain from using different CCs is high enough to outweigh a 50% spectral loss. Where $C(.)$ represents the estimated capacity (throughput) for a given SINR value, and SNR_i is the signal-to-noise ratio (interference excluded) of HeNB i. Since all femtocells implement the same radio access technology, they rely on pre-calculated SINR to throughput mapping tables to derive capacity estimations.

The interference coupling of a pair of cells – right-hand side of (1) – is characterized by the The Background Interference Matrices (BIMs) described in [9], [10]. Basically, a BIM entry is a measurement of signal-to-interference ratio (SIR) for a single interferer. For a pair of cells u and v, $\text{DL}_{\{u\}\leftarrow\{v\}}$ denotes the incoming DL BIM of u and it is a representative value of the SIR experienced by UEs at femtocell u if HeNB v is the only interferer. Conversely, the outgoing DL BIM of u towards v is the SIR measured by UEs at femtocell v, when u is the only interferer. The outgoing BIM is denoted as $\text{DL}_{\{u\}\rightarrow\{v\}}$. Naturally, for a pair of cells the incoming BIM of a cell is the outgoing BIM of the other, i.e., $\text{DL}_{\{u\}\leftarrow\{v\}} \equiv \text{DL}_{\{v\}\rightarrow\{u\}}$, by definition.

Finally, notice that cells need to exchange the incoming BIM values so that relevant interferers are also aware of their outgoing BIMs. This level of information implies a cooperative scenario where communication among neighboring femtocells is possible via e.g. the backhaul. The reliance on UE assistance also limits the direct applicability of this method during the bootstrap. However, nothing precludes the BIM information from being use during reselections or being stored, possibly filtered, and used in subsequential start-ups of the HeNB.

E. Improper Coloring

All three alternatives above are evaluated in the next section. For the last two criteria, two cases were considered:

- Unbounded: No restrictions were imposed and graphs are colored with as many colors as needed.
- Improper coloring: The number of colors, C, is fixed a priori. Each HeNB tries to select a CC differing from those already selected by the $C - 1$ worst-interferers as

seen by the HeNB or served UEs depending on whether the second or third criteria is considered respectively.

An improper coloring means that for each non-isolated $u \in V$, there is at least one vertex v such that $\{u, v\} \in E$ and $c(u) \neq c(v)$. Clearly, it makes little sense to talk about improper colorings for the random criterion due to the way the resulting graph is defined. The main advantage of improper coloring is that it inherently knows when to "stop". Fully autonomous HeNBs attempting a proper coloring could reselect CCs ad-infinitum because they simply might not realize they are trying to solve an impossible problem due to their limited knowledge. For example, the HeNBs might be part of a clique of size 4 and have only 3 CCs to choose from.

IV. Numerical Results

A. Simulation Assumptions

We consider equal rights dynamic spectrum sharing among CSG femtocells. We investigate only the intra-tier interference avoidance, hence macrocells are assumed to operate in a separate band. The performance was evaluated through semi-static system level simulations. The basic LTE physical layer specifications [12] is the basis for the simulator. We derive our results from a Monte Carlo performance evaluation and thousands of snapshots have been simulated to ensure statistical reliability. During each snapshot, path loss, shadowing and the location of devices remain constant. Fast fading is not explicitly simulated.

The simulation scenario and indoor path loss modeling follow that defined in [13] for the dense urban dual-stripe deployment. Three floors 3 floors are simulated, thus totaling 120 apartments. Both HeNBs and UEs are dropped uniformly at random indoor positions. It is assumed that HeNBs are present in 100% of the apartments in order to simulate a challenging scenario, especially when a limited number of colors is considered.

We consider a full buffer traffic model and a 2x2 antenna configuration for all links allowing up to two code words. The transmit power of femtocells was set at 20 dBm. A simple equal resource sharing (round-robin) packet scheduling algorithm is assumed. Error vector magnitude (EVM) modeling is included (5%), thus SINR is asymptotically limited. The SINR values are calculated per physical resource block (PRB) for every simulation step. Look-up tables map the SINR to corresponding throughput values according to a modified Shannon's formula from [14].

B. Greedy Coloring Algorithms

The numerical results were obtained as follows. In each snapshot, the deployed HeNBs were activated; one at a time in a arbitrary sequence given by "Nature", and a single base component carrier (BCC) had to be selected. The resulting graphs for the criteria in Sections III-C and III-D are colored using greedy coloring algorithms. Recap that the coloring algorithm is irrelevant in the random assignment of CCs.

Greedy coloring assigns the first non-conflicting color based on the colors already assigned to pre-existing transceivers. This class of coloring algorithms is suitable for online applications, however it is also well known that the actual number of colors used depends on the chosen ordering and that ordering the vertices according to their degrees reduces the number of colors required [7]. In view of that, colorings where the nodes are ordered using a heuristic based on the descending degree, $deg(v)$, of a vertex are also simulated. The coloring starts with the femtocell with the largest degree. The rationale is that femtocells with less interfering neighbors are "easier" to color [2]. Additionally, in the improper case described in Section III-E, one modification is considered in order to improve the overall quality of the CC selection procedure. Whenever possible, each node picks a random color out the available (non-conflicting) ones instead of always selecting the first available color. This is an attempt to make the partition of vertices among the different colors as uniform (equitable) as possible.

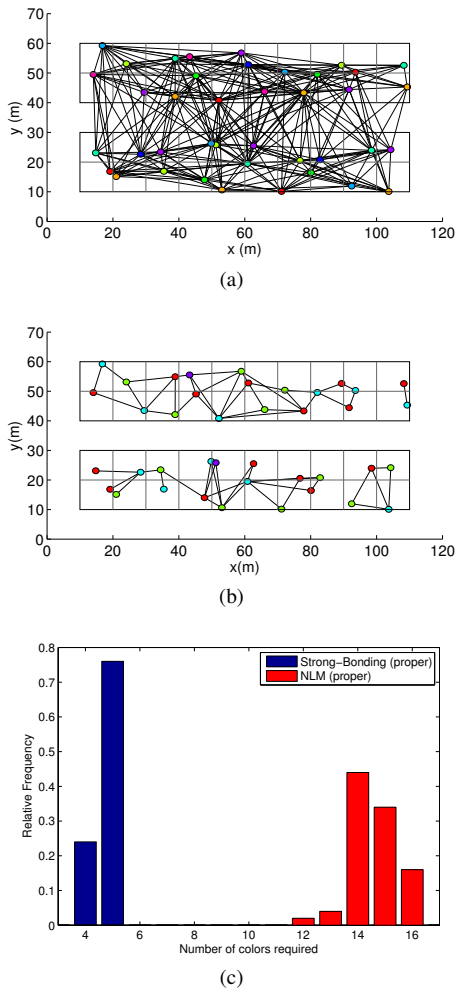
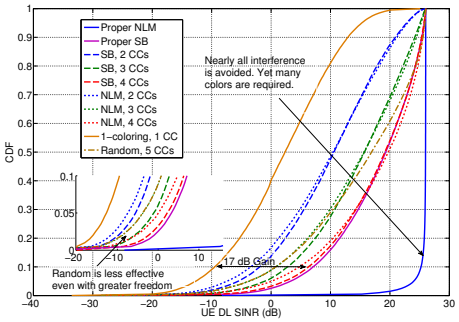
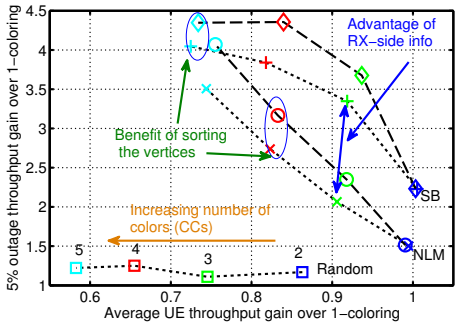


Fig. 2. Analyzing the resulting graphs of two different adjacency criteria for the same topology (single floor).(a): NLM worst-case condition (k=9). (b): Strong-bonding condition (k=4). (c) Histogram of the required number of colors for proper coloring for both criteria when 3 floors are simulated.

[2]In order to rank the vertices according to their degrees, global knowledge of the graph is typically needed. This is generally not a valid assumption. However, this case is included primarily for completeness.



(a)



(b)

Fig. 3. Comparing the performance of the three adjacency criteria.(a): The DL SINR behavior for different criteria and variable number of CCs to choose from. (b): The overall performance of all three strategies when the bandwidth is split into an increasing number of CCs (2-5). The connecting dotted lines depict trend in case of online coloring without sorting the vertices, while the dashed lines show the case of vertices ranked by their degree.

C. Results and Analysis

Results are summarized in Figs. 2 and 3. The former provides some intuition of the impact of the NLM and strong-bonding (SB) based criteria. The random one is not depicted since no insight is gained from overlaying the graph with the deployment layout. It can be seen that when receiver-side information is considered, the resulting graph is significantly sparser, thus requiring a much lower number of CCs to be properly colored as shown in Fig.2c. Proper coloring with fewer CCs is highly advantageous, given that the number of carriers is always limited, and bandwidth splitting takes its toll on capacity. As a result, the fantastic performance of the unbounded NLM method in terms of SINR observed in Fig. 3a cannot be translated into throughput performance. One can also observe: (i) that the SINR performance of the random coloring is significantly worse even when a higher number of CCs is considered. (ii) The C-improper coloring based on the SB criterion leads to better SINR performance than its NLM counterpart, especially in the lower tail of the distribution. (iii) Finally, with 4 CCs the improper SB coloring is virtually as good as the proper coloring. The equitable coloring heuristic contributes to that too.

Finally the overall throughput comparison is presented in Fig. 3b. The fixed system bandwidth was split into three four and five CCs, represented by the blue, green and red markers respectively. Performance is normalized with respect to that of the undivided band, i.e. a single choice. Only improper colorings are depicted. By looking at the performance of the random strategy it can be concluded that it is sensible to preclude event/condition-driven CC reselections completely if the information available is very limited. Moreover, the benefit from sorting the vertices – which is complex in practice – is highlighted and shown to be less than that of using richer receiver-side information. Consequently if infrequent periodic reselection (recoloring), for example once per day or week, is admissible, using receiver-side information seems definitely reasonable given our experimental results.

V. Concluding Remarks

In this paper we studied carrier-based inter-cell interference coordination schemes framed as a graph coloring problem. We compared by means of system level simulations three criteria defining the the edges of a graph representing the network. Proper and improper graph coloring have been investigated. Our results clearly demonstrate that improper coloring methods can achieve most of the benefits of unrestricted off-line coloring algorithms with a very modest number (2-3) of CCs to choose from. The gap between proper and improper coloring is expected to be even smaller if bursty traffic is considered.

References

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update,2010-2015," White Paper, February 2011.

[2] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," *Communications Surveys Tutorials, IEEE*, vol. 3, no. 2, pp. 10–31, 2000.

[3] M.-L. Cheng and J.-I. Chuang, "Performance evaluation of distributed measurement-based dynamic channel assignment in local wireless communications," *Selected Areas in Communications, IEEE Journal on*, vol. 14, no. 4, pp. 698–710, May 1996.

[4] M. Serizawa and D. Goodman, "Instability and deadlock of distributed dynamic channel allocation," in *Vehicular Technology Conference, 1993 IEEE 43rd*, May 1993, pp. 528–531.

[5] L. Narayanan, *Channel Assignment and Graph Multicoloring*. John Wiley & Sons, Inc., 2002, pp. 71–94.

[6] Furqan Ahmed and Olav Tirkkonen and Matti Peltomäki and Juha-Matti Koljonen and Chia-Hao Yu and Mikko Alava, "Distributed Graph Coloring for Self-Organization in LTE Networks," *Journal of Electrical and Computer Engineering*, vol. 2010, August 2010.

[7] J. L. Gross and J. Yellen, *Graph Theory and Its Applications*. Chapman and Hall/CRC, 1999.

[8] M. Huson and A. Sen, "Broadcast scheduling algorithms for radio networks," in *Military Communications Conference, 1995. MILCOM '95, Conference Record, IEEE*, vol. 2, Nov. 1995, pp. 647–651 vol.2.

[9] L. Garcia, K. Pedersen, and P. Mogensen, "Autonomous component carrier selection: interference management in local area environments for lte-advanced," *Communications Magazine, IEEE*, vol. 47, no. 9, pp. 110–116, 2009.

[10] L. Garcia, G. Costa, A. Cattoni, K. Pedersen, and P. Mogensen, "Self-Organizing Coalitions for Conflict Evaluation and Resolution in Femtocells," in *GLOBECOM 2010, 2010 IEEE Global Telecommunications Conference*, dec. 2010, pp. 1–6.

[11] K. Doppler, M. Moisio, and K. Valkealahti, "On interference management for uncoordinated LTE-Femto cell deployments," *Wireless Conference 2011 - Sustainable Wireless Technologies (European Wireless), 11th European*, pp. 1 –6, april 2011.

[12] 3GPP, "TR 25.814, Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA), V 7.1.0," Tech. Rep., September 2006.

[13] 3GPP , "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects," Tech. Rep. 36.814 v9.0.0, March 2010.

[14] P. E. Mogensen *et al.*, "LTE Capacity Compared to the Shannon Bound," in *VTC Spring*, April 2007.