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Simulated annealing variants for self-organized resource allocation in small cell networks

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ABSTRACT

This paper discusses the application of simulated annealing (SA) based meta-heuristics to self-organized orthogonal resource allocation problems in small cell networks (SCN)s, for static and dynamic topologies. We consider the graph coloring formulation of the orthogonal resource allocation problem, where a planar graph is used to model interference relations in a SCN comprising of randomly deployed mutually interfering cells. The aim is to color the underlying conflict graph in a distributed way, for which different variants of SA such as SA with focusing heuristic (i.e., limiting the local moves only to the cells that are in conflict), and fixed temperature, are investigated. For static topologies, distributed algorithms are used, in which no dedicated message-passing is required between the cells, except for the symmetrization of conflict graph. To enable distributed SA in dynamic topologies, a distributed temperature control protocol based on message-passing is considered. Different aspects relevant to self-organizing cellular networks are analyzed using simulations. These include the number of cells with resource conflicts, number of resource reconfigurations required by the cells to resolve the conflicts, requirements on dedicated message-passing between the cells, and sensitivity to the temperature parameter that guides the stochastic search process. Simulation results indicate that the considered algorithms are inherently suitable for SCNs, thereby enabling efficient resource allocation in a self-organized way. Furthermore, the underlying concepts and the key conclusions are general, and relevant to other problems that can be solved by distributed graph coloring.

1. Introduction

Self-organization in wireless networking entails functionalities that ensure ubiquitous network connectivity and scalability, whilst guaranteeing the desired quality of service to the served users [1]. In the context of contemporary cellular systems such as Long Term Evolution (LTE)/LTE-Advanced (LTE-A), the self-organizing networking (SON) paradigm encompasses mechanisms for self-configuration, self-healing, and self-optimization [2]. As the cellular networks are becoming increasingly complex due to massive deployments of small cells, a multitude of challenges related to network resource allocation, management, and operation have emerged. SON mechanisms address these challenges by enabling automated optimization of network parameters and reduction in capital/operational expenditure.

The importance of SON in future networks is underscored by the fact that the vision for 5G entails diverse use-cases, involving both cooperative and non-cooperative scenarios. For fully cooperative scenarios, virtualization of network resources is under consideration, which involves abstraction of multiple network management functions to network graphs for software-based control [3]. On the other hand, resource allocation problems in non-cooperative scenarios, such as multiple-operators sharing spectrum in authorized shared access and multiple technologies sharing unlicensed spectrum are inherently more challenging, and will require SON algorithms which do not involve any dedicated message-passing between the nodes. Moreover, in large-scale networks, computation of an optimal resource allocation is prohibitively complex, especially under dynamically changing topologies, as it requires the availability of complete information regarding the network state at every node. Local decisions based on limited information, computation capabilities, and inter-cell signaling are thus inevitable, and motivate the application of self-organizing algorithms.

A number of existing SON mechanisms in cellular networks involve self-organized allocation of orthogonal resources among cells. Notable examples include primary component carrier (PCC) selection [4,5], physical cell ID (PCI) assignment [5,6], and the classical frequency assignment problem [7]. These can be modeled as graph coloring problems, where vertices represent the cells and colors are the available resources. The aim is to color the underlying interference graph such that no two adjacent cells use the same resource. Thus, resource allocation problems are of due importance for both contemporary and future cellular networks, and mandate the study of new self-organizing algorithms, tailored to the requirements of SCNs. Generally, self-organized resource allocation in wireless networks involves computing a solution to an underlying network optimization problem, using distributed algorithms [8,9]. For discrete problems such as orthogonal resource allocation on an interference graph, combinatorial optimization methods involving metaheuristics are an attractive option. Accordingly, distributed algorithms based on metaheuristics can pave the way for engineering self-organizing solutions to discrete resource allocation problems in SCNs.

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In this paper, we study different variants of the Simulated Annealing (SA) metaheuristic for self-organized resource allocation in SCN, under static as well as dynamic topologies. To this end, different parameters and performance indicators important from a perspective of SCNs are taken into account, in the design and analysis of algorithms. It is assumed that the resources are orthogonal, which leads to a generic system model applicable to a number of SON problems. The algorithms investigated are SA with *focused search* enhancements [10], which focuses uphill and/or plateau moves only on the cells which are in conflict with their respective neighbors. Furthermore, the overall concept can be considered as a generic framework for distributed resource allocation under limited information and dynamic topology. In the remaining part of this section, we give a brief description of the state-of-the-art of SA based methods in wireless networks, followed by a summary of the contributions of this work.

1.1. Related work

The well known SA based optimization methods essentially balance *exploration* and *exploitation* to search the solution space in an efficient manner. In particular, the hill-climbing feature and the plateau moves play a key role in escaping from local minima and long plateaus, whereas downhill moves ensure attraction to the global optimum. Frequency of uphill moves is controlled via a temperature parameter which is set before-hand, and is reduced according to a cooling schedule as the algorithm progresses [11].

In wireless networking domain, SA has been discussed for distributed channel allocation in wireless local area networks [12], where each access point is assigned a sigmoidal utility function, parametrized by the interference level it experiences. A similar approach proposed in [13], minimizes the total interference in the network, and is shown to outperform the Leith and Clifford algorithm [14]. SA for uplink power control in LTE-A networks is discussed in [15], and for power optimization of pilot signals in [16,17]. Other resource allocation problems in cellular networks addressed using SA include downlink scheduling in LTE networks [18], handover parameter optimization in LTE networks [19], and antenna-tilt optimization [20].

To develop the SA based methods for the orthogonal resource allocation problem, we consider the graph coloring model, where the aim is to assign resources to cells in a non-conflicting way. The minimization of resource conflicts in the network translates to mitigation of cross-channel interference between the cells. This work can be considered as an extension of [12,13], however, our focus is on the soft computing aspects and different variants of SA, which are pertinent to self-organization in SCNs.

1.2. Contributions

We seek to minimize the number of resource conflicts among the cells, as well as the number of resource reconfigurations in the SCN, for both static and dynamically changing topologies. It is important from the perspective of a SCN that both the cells with conflicting resources, and total reconfigurations incurred while resolving those conflicts, are minimized. The first SA variant, we discuss, comprises of SA metaheuristic combined with the *focused search* mechanism [21,10], which allows uphill/plateau moves only to the cells that are in conflict. Existing works discuss SA with a cooling schedule, where temperature is considered as a network parameter. This introduces a centralized component in the procedure, and is therefore not suitable for SCNs which often have dynamic topologies. Thus, we introduce the fixed temperature alternative [22,23], which is *fully distributed* as it does not require any cooperation between cells. It is observed that the fixed temperature variant performs better than the standard SA algorithm. The second variant is motivated by the practical issue of minimizing the reconfigurations of cells in a network, and it involves focusing plateau moves only on the cells that are in conflict. Similar variants that involve combined focusing of plateau moves and uphill moves are also considered. To determine the optimal noise strategy (temperature) for coloring problem, we compare fixed temperature SA variants to their cooling counterparts across a wide range of temperatures. Furthermore, we discuss distributed temperature control protocols for applying SA to dynamic networks. The discussed algorithms have different characteristics related to plateau moves, uphill moves and downhill moves, which results in varying performance in different scenarios, when applied to the graph coloring problem.

The rest of the paper is organized as follows: Section 2 introduces the system model along with an overview of distributed graph coloring concept, and properties of planar graphs. Section 3 involves discussion on SA for orthogonal resource allocation, and related self-organizing algorithms for SCNs. In Sections 4 and 5, comparison of the considered algorithms is carried out by simulations, for static and dynamic networks, respectively. Finally, conclusions are given in Section 6.

2. System model

The motivation for applying metaheuristics for self-organized allocation of orthogonal resources (e.g., channels, PCCs, PCIs) in cellular networks stems from the fact that in such cases graph coloring models can be readily applied. In fact, graph coloring is a well studied problem, and both centralized as well as distributed graph coloring approaches exist. These approaches may be applied to SCNs, provided that the assumptions on computation and inter-cell communication aspects of the system are reasonable. In this regard, the distributed graph coloring approaches have gained considerable popularity, because of their promising features well suited to the needs of SCNs.

2.1. Distributed graph coloring

Graph coloring is an NP-complete combinatorial optimization problem, with a wide range of applications, see for example [24,25]. Centralized coloring approaches based on SA are discussed in [26,27]. Another important metaheuristic is Tabu search [28], which avoids being trapped in local minima by maintaining a list of bad moves, and updating them during iterations. For large graphs, pure local search methods may not work efficiently. Such graphs can be colored by using stable set extraction as a first step, followed by using local search on residual graph. Another important approach is genetic optimization combined with local search, which leads to hybrid algorithms [29,30]. A detailed survey of local search algorithms for graph coloring, along with classification of different local search strategies is given in [31]. The distributed approaches have seen a steady rise in popularity due to their practical applications in different areas, for details see [32], and references therein. For distributed coloring, local search methods as well as distributed constraint satisfaction algorithms are relevant [33,34]. Fully distributed algorithms are particularly important for self-organized coloring. These algorithms work in a way that each node of the graph makes the decisions regarding its color, on the basis of local information only. This motivates their application for self-organized resource allocation in the SCNs.

2.2. Network model: interference graphs and Voronoi tessellations

We consider a planar graph model for a SCN comprising of low power cells deployed randomly, in a given geographical area. A cell considers a neighboring cell to be an interferer if the interference received from it is greater than a given threshold. The threshold models the measurement and reporting capabilities of the users served by the cell. The neighbor relations among the cells are based on the mutual interference which is predominantly dependent on their spatial separation. Thus, an interference graph can be created via thresholding, where the cells are the vertices, and the edges represent the interference couplings between them. These interference couplings may be symmetrized in the cellular networks in which a backhaul connection exists between the cells (e.g., LTE/LTE-A). The resulting interference graph is undirected, so that a conflict can be seen by both cells. Alternatively, for SCNs deployed on a 2D plane, an effective approach is to use planar graph model [35,36]. This model is particularly accurate under the assumptions that non-distance dependent propagation effects such as shadow fading are mild. Consequently, the interference couplings are considered only between the cells that are neighbors geographically, as they would be measured and reported as strong potential interferers by the users. In this case, each user in the network coverage area will connect to the closest base-station (cell), i.e., the base-station with the minimum Euclidean distance, whereas the points equidistant from multiple base-stations may pick their serving base-station randomly. This results in a Voronoi tessellation of the coverage area, which is planar by definition. In order to create such graph, we consider a square-shaped coverage area and drop N_v points $v \in \mathcal{V}$ at random in it, and compute the Voronoi tessellation corresponding to those points. The coverage area is split into Voronoi cells, where each cell constitutes the area consisting of the points that are