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A PCI planning algorithm for jointly reducing reference signal collisions in LTE uplink and downlink

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ABSTRACT

In this paper, a novel automatic planning method is proposed for allocating Physical Cell Identifiers (PCI) to cells in a Long Term Evolution (LTE) system based on handover and cell load measurements. The method aims at avoiding PCI collision and confusion problems, while reducing Reference Signal (RS) collisions between neighbor cells. For this purpose, the problem is formulated to consider RS collisions both in DownLink (DL) and UpLink (UL). Then, a classical graph partitioning algorithm is adapted to solve the graph coloring problem behind PCI planning. The considered algorithm is the multi-level version of the Fiduccia and Mattheyses local refinement algorithm. Performance assessment is carried out on graphs constructed from data collected in live LTE network. Results show that the proposed algorithms can avoid PCI collision and confusion problems, while reducing DL RS collisions and almost eliminating UL RS collisions compared to a random plan.

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1. Introduction

In recent years, the evolution of mobile networks has led to a significant increase in network system requirements and complexity. Therefore, network operators seek automated solutions for operation and maintenance tasks to minimize the workload and errors due to human interaction. This justifies that the new Long Term Evolution (LTE) standard is known for its self-organization features, which include capabilities for self-planning, self-optimization and self-healing [1].

In LTE, Physical Cell Identifier (PCI) planning has been identified as an important use case for self-planning [2,3]. A PCI is a low-level cell signature used to identify cells in mobility procedures, such as handovers or cell reselection [4]. The number of possible PCI values is limited, which forces several base stations to share the same PCI. As a result, a wrong assignment of PCIs may cause that two adjacent cells use the same PCI (problem referred to as *collision*) or a serving cell has two neighbors with the same PCI (referred to as *confusion*) [1]. Both issues prevent users from detecting target cells, causing that no radio communication is possible. Therefore, proper PCI allocation is essential for an adequate service performance. Such an allocation is a non-trivial task due to the limited number of PCIs.

At the same time, PCI determines the location in time and frequency of DownLink (DL) signaling channels, amongst which are DL Cell-specific Reference Signals (CRS), and the specific set of Demodulation Reference Signals (DM RS) in UpLink (UL).

In DL, CRSs are transmitted in different subcarriers depending on the PCI assigned to the cell. Thus, each cell has a specific pilot pattern corresponding to its cell identity. The number of possible pilot patterns depends on the antenna configuration, but it is always less than 6 [5], causing that CRSs of surrounding cells often collide. CRS collisions degrade Signal-to-Interference-plus-Noise Ratio (SINR) estimates, reported by the User Equipment (UE), which are used by the eNB to select the modulation and coding scheme (MCS) for DL transmission. Thus, an improper PCI planning may give inaccurate SINR estimates, which leads to inefficient data transmission in the DL [6].

In UL, PCI defines the set of DM RSs transmitted by users, used by the base station for channel estimation and coherent demodulation in the Physical Uplink Shared Channel (PUSCH) and Physical Uplink Control Channel (PUCCH) [5]. If two users of different cells use the same DM RS, the decoding process in PUCCH or PUSCH is degraded, which might cause that the base station could not identify the user correctly. As described in [7], the definition of DM RSs in PUSCH can be decoupled from PCI planning, and, thus, DM RS design can be optimized independently to the PCI plan design.

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However, this is not the case for PUCCH, where DM RSs can only be controlled by PCI planning.

Then, the benefits of considering Reference Signals (RS) in PCI planning are: a) in the DL, improved channel estimates, and, hence, better radio link efficiency, leading to higher DL user throughput and larger network capacity, and b) in the UL, a reduced PUCCH failure rate, which leads to lower UL delays due to less retransmissions and higher DL throughput due to a more robust Channel Quality Indicator (CQI) reporting.

In the literature, most PCI planning approaches are designed to avoid collision and confusion problems [8–10]. With these two objectives, PCI planning is usually formulated as a graph coloring problem, which can be solved by graph theoretic algorithms (e.g., greedy algorithm) [8,9] or general-purpose discrete optimization algorithms (e.g., random search, simulated annealing, tabu search, genetic algorithms, constraint satisfaction algorithms, linear programming, ...) [11]. Preliminary studies considered centralized PCI planning schemes [12] and later studies evaluate distributed versions [9,13–15]. Recent works have extended the analysis of PCI planning to heterogeneous LTE networks, consisting of several layers, by considering collision and confusion between cells of different layers [16–24]. Also, recent works have extended the PCI planning use case to emerging scenarios relevant to 5G, e.g., multi-operator [25] and ultra-dense network [26] scenarios. Moreover, considering UL RS collisions when assigning PCIs in 5G networks will be of the utmost importance, as UL performance is critical in machine type communications for Internet-of-Things applications [27]. However, none of these studies consider DL CRS or UL DM-RS collisions. Only in [28], a simple PCI planning method is proposed to reduce DL CRS collisions between cells of the same site. The method does not avoid DL CRS collisions between non-cosited adjacent cells, nor does it consider UL DM-RS collisions. Likewise, a centralized PCI planning scheme based on a genetic algorithm is proposed in [29] to avoid CRS collisions and thus improve network coverage and DL user throughput.

To the authors' knowledge, no PCI planning method has considered UL and DL RS collision together with PCI collision-confusion problems. As shown later, building a PCI plan for just one of these criteria leads to solutions with suboptimal performance in terms of the other criteria. Likewise, classical PCI planning methods often rely on heuristic graph coloring algorithms that must be designed from scratch with the subsequent developing effort. Moreover, previous PCI planning approaches are based on estimates built by radio network planning tools, and do not make the most of performance statistics in the network management system.

In this work, a novel formulation of the PCI planning problem is presented that considers UL and DL CRS collisions problems as well as PCI collision-confusion problems. In the proposed approach, problem instances are constructed from live network measurements. Unlike previous work, the graph coloring problem in PCI planning is re-formulated as a graph partitioning problem, for which very effective codes exist in the public domain (e.g., METIS [30], JOSTLE [31], Chaco [32]). Then, PCI planning is solved by a multi-level refinement graph partitioning algorithm, which is the common benchmark against which other graph partitioning methods are compared [33–35]. Finally, the method is validated with a problem instance taken from a real LTE network.

The rest of the paper is organized as follows. Section 2 presents the new formulation of the PCI planning problem that also considers RS collisions, which is the main contribution of this work. Section 3 presents the proposed multi-level refinement graph partitioning algorithm. Section 4 presents the results of the PCI planning method in a real problem instance. Finally, Section 5 presents the main conclusions of the study.

2. Problem formulation

This section begins with the basics of PCI assignment in cellular networks. Then, the proposed graph-theoretic formulation of the PCI planning problem is presented. Finally, the problem is reformulated as a graph partitioning problem.

2.1. PCI planning in cellular networks

The PCI is obtained by the UE from the Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS). From SSS, the UE obtains the physical layer cell identity group index, $N_{ID}^{(1)}$ (ranging from 0 to 167). From PSS, the UE obtains the physical layer identity index, $N_{ID}^{(2)}$ (ranging from 0 to 2) [5]. Then, the PCI is defined as:

$$PCI(i) = 3 \cdot N_{ID}^{(1)}(i) + N_{ID}^{(2)}(i), \tag{1}$$

ranging from 0 to 503. The number of unique PCI values is limited to 504, so these have to be reused across the network. Such a reuse of PCIs leads to different problems.

A first issue happens when a UE is in the coverage area of two cells sharing the same PCI. This UE may not be able to identify its serving cell. As a result, radio channel information may not be correctly decoded. This problem is referred to as a *collision* event. A second issue occurs when a UE is camped in a serving cell and two neighbor cells share the same PCI. In this case, the target cell would not be identified properly when a handover is executed. This problem is referred to as a *confusion* event. A good PCI plan should avoid collision and confusion problems assigning the same PCI value to quite distant cells.

In addition to avoiding PCI collision and confusion, a proper PCI plan can increase DL and UL transmission efficiency by reducing RS collisions.

In DL, PCI defines the allocation of CRSs along the Physical Resources Blocks (PRBs) in time and frequency. PRB is the minimum unit of resource allocation in LTE, consisting of a bandwidth of 180 kHz and a time interval of 0.5 ms.

Fig. 1 shows the CRS pattern in time and frequency for 1 PRB and 1 Transmission Time Interval (TTI), with normal cyclic prefix. Squares in the figure represent the different Resource Elements (REs), each consisting of the combination of a subcarrier and an OFDM symbol. Dark squares correspond to REs reserved for CRSs, while white squares correspond to REs reserved for data transmission. In the time domain, CRSs are transmitted in the same Orthogonal Frequency Division Multiplexing (OFDM) symbol of the frame structure in all cells, regardless of the PCI value. However, in the frequency domain, CRSs are allocated to different subcarriers depending on the PCI value of the cell. The number of possible CRS allocation patterns depends on the antenna configuration. As observed in Fig. 1(a), when using one antenna port (i.e., Single Input Single Output -SISO- or Single Input Multiple Outputs -SIMO- schemes), 6 CRS allocation patterns are possible. The specific pattern in a cell is given by the PCI of the cell by the operation *PCI* mod 6. In case of two or four antenna ports (i.e., Multiple Inputs Single Output -MISO- or Multiple Inputs Multiple Outputs -MIMO- schemes), shown in Fig. 1(b), the CRS allocation pattern is given by the operation *PCI* mod 3, which coincides with the value of PSS in the cell.

When two cells have the same CRS allocation pattern, CRS collisions degrade DL Signal-to-Interference-plus-Noise Ratio (SINR) estimates. The reason is that the UE assumes that interference in data channel is as high as that experienced in REs where CRS are allocated, which is not necessarily true. SINR estimates are reported by the UE to the eNodeB (eNB) and used later to select the modulation and coding scheme (MCS) for DL transmission. Therefore, if a CRS collision occurs between neighbor cells as a result

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