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Performance evaluation of intra-site coordination schemes in cellular networks

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ABSTRACT

In this work, we develop performance evaluation models for some intra-site coordination schemes in cellular networks, with a focus on Multi-flow transmission in HSPA+. We first focus on a static scheme where coordination is always performed for all users in the overlapping region of two cells. Through the analysis of a flow-level model, we show that this scheme indeed improves the cell-edge throughput at low loads but may make the system unstable at high loads, due to the suboptimal allocation of radio resources. We notice also that these results are very sensitive to the coordination threshold. We thus investigate a dynamic scheme which performs coordination according to resource availability in the site and show that this scheme outperforms the static one at all traffic loads independently of the coordination threshold. Additional results demonstrate an efficient load balancing ability across cells. We finally analyze how our models extend to the case of opportunistic scheduling schemes, like Proportional Fair, and show the impact of these schemes on the coordination gains.

1. Introduction

Inter-cell interference is a major issue in cellular networks, especially with frequency reuse one. It does not only make users at the cell edge suffer from low throughputs but also decreases the overall network capacity since these users consume a significant proportion of the radio resources [1]. Cell coordination has been proposed as an efficient way for reducing inter-cell interference by either silencing some base stations or allowing several base stations to transmit data simultaneously to the same user [2].

Recently, it has been adopted by 3GPP standards for Beyond 3G networks. Release 11 introduced cell coordination for High Speed Packet Access (HSPA+) systems in the Multipoint transmission feature including three main techniques: the single point data transmission, the multi flow data transmission and the single frequency network data transmission [3]. In LTE-Advanced, cell coordination is included in Release 11 under the name of Coordinated MultiPoint (CoMP) [4]. Two main categories are proposed: the joint processing scheme and the joint scheduling/ beamforming scheme.

There are two broad classes of cell coordination schemes: inter-site coordination, where cells of different sites are coordinated, and intra-site coordination, where cells (or sectors) of the same site are coordinated [5,6]. Inter-site coordination remains extremely challenging to implement for several reasons related mainly to the backhaul limitations.

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Thus, we focus on intra-site coordination which is much simpler and more practical since all scheduling decisions are local so there is no additional signaling overhead to be considered.

The major challenge of cell coordination is to control the strong coupling of scheduling decisions in the different cells. Indeed, scheduling a user in a given cell may prevent users in neighboring cells to be served, leading to the following dilemma:

1. Cell coordination increases substantially the data rates of users when scheduled.
2. Cell coordination leads to situations where only few users are simultaneously scheduled in the network, thus decreasing the proportion of time where individual users are scheduled.

This tradeoff between higher achievable rates (due to lower interference) and higher radio resource consumption (due to silences or joint transmissions to the same user) is arguably the key issue when designing a coordination scheme.

The present work aims at evaluating the performance of intra-site coordination in cellular networks by addressing this tradeoff analytically, and numerically in a HSPA+ system. We start by investigating a static scheme where coordination is always performed in the overlapping area between two cells. We show in particular that this scheme improves cell-edge throughput at low loads but may make the system unstable at high loads, due to the suboptimal allocation of radio resources. We notice also that these results are very sensitive to the coordination area size. Hence, we investigate a dynamic scheme which performs coordination according to the resource availability in the site in the different sectors and we show that it outperforms the static one in all load situations, independently of the coordination area. Additional results demonstrate an efficient load balancing ability across cells. Finally, we investigate the impact of opportunistic scheduling algorithms on the coordination gains.

In summary, the main contributions of this paper are threefold:

- We develop an analytical framework for evaluating the performance of intra-site coordination in terms of throughput and load balancing.
- We analyze two different coordination schemes and their ability to improve cell edge throughput while preserving the system stability at high loads.
- We provide numerical performance results for a HSPA+ system.

The remainder of this paper is organized as follows. We start by presenting the related work. Then, we describe the cell coordination schemes. We present the model and we analyze performance in the absence of coordination in Sections 4 and 5. Sections 6 and 7 are dedicated to the performance analysis of the static and dynamic schemes, respectively. In Section 8, we investigate the impact of opportunistic scheduling algorithms on the coordination gains. Section 9 concludes the paper.

2. Related work

The idea of cell coordination was originally used in cell breathing methods applied to multiple cellular networks [7] which allows overloaded cells to offload traffic to neighboring cells and more explicitly in the soft handover mechanism in a WCDMA system where a user is simultaneously associated to two or more base stations in order to enhance the system performance in terms of QoS and coverage [8].

Recently, within the framework of Release 11 of HSPA+ [3], the concept of Multi-point transmission has been introduced. It is expected to enhance user experience by improving network performance, especially at the cell edge, and efficiently balancing load between cells as it has been shown in several studies, see e.g. [9–11] and references therein. Equivalently, Release 11 of LTE-Advanced system has adopted the Coordinated MultiPoint transmission as a key feature among with other advanced technologies such as Multi-User MIMO (see [5,12] for instance).

The first attempts to evaluate the performance of coordination schemes (see e.g. [2] and references therein) focused on physical layer aspects and were based on so-called full buffer simulations, as proposed by 3GPP [13]. In this approach, a fixed number of users is simulated in each cell with a nearly complete emulation of the physical and MAC layers. The advantage of these simulations is their high accuracy with respect to the lower layers as they take into account a complete channel model including path loss, shadowing and fast fading. However, they do not capture the dynamic aspect of traffic, which is critical for the performance of coordination schemes.

Due to this shortcoming, so-called finite buffer simulators have been recently proposed (see the FTP simulation model in [13]). These simulations add the dynamic traffic layer whereby short-lived data flows are generated at random times, mimicking the user behavior. Such simulations have recently been used in [14] to evaluate the performance of coordination schemes in HSPA networks and in [15] to analyze its ability to balance load. Substantial throughput gains from coordination are observed, especially at the cell edge. Although finite buffer simulations provide useful insights into the efficiency of coordination schemes, they are computationally intensive, especially when stability issues are addressed.

Analytical methods are practically interesting and, to the best of our knowledge, have not yet been proposed in the considered dynamic setting with flow arrivals and departures. Indeed, the underlying model corresponds to a set of coupled queues, which is known to be intractable beyond some very specific cases [16]. Bounds and approximations for the impact of inter-cell interference on user throughput have been derived in [17–21]. In [22], flow level Markovian analysis was used to evaluate the performance of coordination using LTE-Advanced codebook-based schemes jointly with Multi user diversity. Such studies are very relevant but are not scalable.