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Cooperative Wireless Cellular Systems: An Information-Theoretic View

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Abstract

In this monograph, the impact of cooperation on the performance of wireless cellular systems is studied from an information-theoretic standpoint, focusing on simple formulations typically referred to as Wyner-type models. Following ongoing research and standardization efforts, the text covers two main classes of cooperation strategies. The first class is cooperation at the base station (BS) level, which is also known

as Multi-Cell Processing (MCP), network Multiple-Input Multiple-Output (MIMO), or Coordinated Multi-Point transmission/reception (CoMP). With MCP, cooperative decoding, for the uplink, or encoding, for the downlink, is enabled at the BSs. MCP is made possible by the presence of an architecture of, typically wired, backhaul links connecting individual BSs to a central processor (CP) or to one another. The second class of cooperative strategies allows cooperation in the form of relaying for conveying data between Mobile Stations (MSs) and BSs in either the uplink or the downlink. Relaying can be enabled by two possible architectures. A first option is to deploy dedicated Relay Stations (RSs) that are tasked with forwarding uplink or downlink traffic. The second option is for the MSs to act as RSs for other MSs.

MCP is first studied under ideal conditions on the backhaul links, namely by assuming that all BSs are connected to a CP with unlimited-capacity links. Both Gaussian (nonfading) and flat-fading channels are analyzed, for the uplink and the downlink, and analytical insights are drawn into the performance advantages of MCP in different relevant operating regimes. Performance comparison is performed with standard Single-Cell Processing (SCP) techniques, whereby each BS decodes, in the uplink, or encodes, in the downlink, independently, as implemented with different spatial reuse factors. Then, practical constraints on the backhaul architecture enabling MCP are introduced. Specifically, three common settings are studied. In the first, all the BSs are connected to a CP via finite-capacity links. In the second, only BSs in adjacent cells are connected via (finite-capacity) backhaul links. In the third, only a subset of BSs is connected to a CP for joint encoding/decoding (clustered cooperation). Achievable rates for the three settings are studied and compared for both the uplink and the downlink.

The performance advantages of relaying are analyzed for cellular systems with dedicated RSs and with cooperative MSs. Different techniques are reviewed that require varying degrees of information about system parameters at the MSs, RSs, and BSs. Performance is investigated with both MCP and SCP, revealing a profound interplay between cooperation at the BS level and relaying. Finally, various open problems are pointed out.

Contents

1

Introduction

In this section, we provide a brief introduction to the subject of this monograph and discuss the goals and outline of the text.

1.1 Motivation

Cooperative communication refers to the coordinated transmission or reception by some nodes of a given communication network (see, e.g., [48]). In the context of wireless cellular systems, cooperation is being currently studied in both academic research activities and standardization efforts in two different forms.

- ***Multi-Cell Processing (MCP)***: The first type of cooperative strategies is at the base station (BS) level, and is known as Multi-Cell Processing (MCP), network Multiple-Input Multiple-Output (MIMO) [122] or Coordinated Multi-Point transmission/reception (CoMP), with the last term being used in the 4th Generation (4G)-Long Term Evolution (LTE)-Advanced cellular standard (see, e.g., [3]). With MCP, cooperative decoding, for the uplink, or encoding, for the downlink, is enabled at the BSs. MCP is made possible by the presence of an architecture of, typically wired, backhaul links connecting individual BSs to a central processor (CP), or to one another.

- ***Relaying***: The second class allows cooperation in the form of relaying for conveying data between Mobile Stations (MSs) and BSs in either the uplink or downlink. Relaying can be enabled by two possible architectures. A first option is to deploy *dedicated Relay Stations (RSs)* that are tasked with forwarding uplink or downlink traffic. The second option is for the MSs to act as RSs for other MSs.

The two approaches have different merits and expected performance gains, as discussed below. Overall, they are seen as extremely promising strategies to overcome the current problem of "bandwidth crunch" affecting cellular systems due to the ever increasing capacity demands [19].

By enabling joint encoding and decoding across multiple cells, MCP has the capability to turn inter-cell interference from one of the main limitations on the system performance, as it is in conventional non-cooperative cellular systems, into an asset. For instance, focusing on the downlink, thanks to inter-cell "interference", MCP enables all the BSs to communicate to any MS in the system in a cooperative fashion. This allows the BSs to control, and potentially cancel, inter-cell interference, and thus to serve the MSs at a rate that is not limited by such interference. Similar considerations apply to the uplink as well.

Beside interference mitigation, through BS cooperation, MCP allows *beamforming, diversity*, and *multiuser diversity* gains to be harnessed. The first of these gains refers to the possibility of performing coherent decoding or encoding across multiple BSs so as to boost the effective signal-to-noise ratio (SNR) in the uplink or downlink. The second, diversity, refers to the possibility of leveraging different signal paths from transmitter to receiver in order to increase the probability the transmitted signal is received with a sufficiently large SNR. The third, multiuser diversity, accounts for the design degrees of freedom afforded by the ability to schedule different users depending on their channel conditions across the whole network.

Relaying, instead, is mostly seen as a way to extend the coverage of a given BS by enabling multihop transmission between an MS and a BS (see, e.g., [55, 110]). Equivalently, it can also be seen as a means to reduce the required transmission energy in the uplink or downlink for given SNR requirements. Relaying also enables beamforming and diversity gains to be harnessed via cooperation between MSs or between MSs and RSs (see, e.g., [51]).

1.2 Approach and Goals

The analysis of MCP was initiated in the early works [33, 132] for the uplink and in [96] for the downlink. The analysis in these works is based on the assumption that the BSs are connected via unrestricted backhaul links (*error-free and unlimited capacity*) to a CP and focuses on models that, in information-theoretic terms, can be seen as *symmetric Gaussian multiple access or broadcast interference channels*. In these models, typically referred to as *Wyner-type models*, a number of users per cell are served by a single-antenna BS, as in a multiple access or broadcast channel, and interference takes place only between adjacent cells, as in partially connected interference networks. Both the models where cells are arranged along a line or in a more conventional bidimensional geometry can be considered, where the first class may model systems deployed along a highway, railroad, or long corridor (see [122] for an implementation-based study), while the second applies to more general scenarios.

Wyner-type models are simple abstractions of cellular systems. They capture well one of the main aspects of such settings, namely the locality of inter-cell interference. The advantage of addressing the study of given transmission strategies on such models is the possibility to obtain analytical insights. These insights provide an invaluable stepping stone for the simulation-based studies that are necessary for a full performance assessment under more realistic operating conditions (see, e.g., [135] for further considerations on this point).

In this monograph, we aim at providing an information-theoretic view of the advantages of cooperation in wireless cellular systems in terms of MCP, relaying and their interplay. In order to enable analysis, we will adopt Wyner-type models. The treatment reviews a number of results available in the literature in a unified fashion that reveals their connections and illuminates general conclusions. We will keep the treatment as self-contained as possible, but we will privilege intuition over analytical details and technicalities. In particular, we will not provide any detailed proof. In doing so, our goal here is to provide an understanding of the performance of the cooperative techniques at hand and of the analytical tools used for this purpose.

As research in the field is still ongoing, the treatment will be far from complete, and we will point to open problems along the way. Nevertheless, we feel that the available results are mature and complete enough to warrant the treatment given in this text. We will provide a clear pointer to the main references used in compiling this monograph. However, we will not attempt to provide a comprehensive bibliography on the subject of cooperation for cellular system. It should also be emphasized that the focus here is based purely on information-theoretic arguments and is limited to Wyner-type models. In particular, we will leave out discussion of other more complex models and of important issues such as the signal-processing aspects of optimal beamforming and power allocation. A more complete list of references in this regard can be found in [28]. Previous shorter tutorials can be found in [92, 93].

1.3 Outline

The text is organized as follows. In Section 2, the models that will be adopted for analysis throughout the monograph are presented. Then, in Section 3, results are discussed that provide the performance of MCP under ideal conditions on the backhaul links, namely by assuming that all BSs are connected to a CP with unlimited-capacity links, and without accounting for fading. Section 4 extends these results from the Gaussian model studied in the previous section to flat-fading channels for both uplink and downlink. Performance comparison is performed with standard Single-Cell Processing (SCP) techniques, whereby each BS decodes, in the uplink, or encodes, in the downlink, independently, as implemented with different spatial reuse factors. In Sections 5 and 6, practical constraints on the backhaul architecture enabling MCP are introduced for the uplink and downlink, respectively. Specifically, three common settings are studied. In the first, all BSs are connected in a CP via finite-capacity links. In the second, only BSs in adjacent cells are connected via (finite-capacity) backhaul links. In the third, only a subset of nearby BSs is connected to a CP for joint encoding/decoding (clustered cooperation). The performance advantages of relaying are finally analyzed for cellular systems with dedicated RSs (Section 7) and with cooperative MSs (Section 8) over Gaussian channels. Different techniques are proposed that require varying degrees of information about system parameters at the MSs, RSs, and BSs. Performance is analyzed with both MCP and SCP, revealing a profound interplay between cooperation at the BSs and relaying.

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