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Excerpt

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Part I

Introduction

1 Network architectures and research issues in cooperative cellular wireless networks

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1.1 Introduction

The systematic study of relaying and cooperation in the context of digital communication goes back to the work of Van der Meulen [1] and Cover and El Gamal [2]. The basic relay channel of [1, 2] consists of a source, a destination, and a relay node. The system models in [1, 2] are either discrete memoryless channels (DMC), or continuous-valued channels which are characterized by constant (nonrandom) links and additive white Gaussian noise.

The study of cooperative *wireless* communication is a more recent activity that started in the late 1990s, and since then has seen explosive growth in many directions. Our focus is specifically on aspects of cooperative communication related to cellular radio. Aside from the fading model, the defining aspects of a cellular system are base stations that are connected to an infrastructure known as the *backhaul*, which has a much higher capacity and better reliability than the wireless links. The endpoints of the system are *mobiles* that operate subject to energy constraints (battery) as well as constraints driven by the physical size of the device that lead to bounds on computational complexity and the number of antennas, among other considerations. There are multiple mobiles in each cell as well as frequency reuse, leading to intracell interference and intercell interference, respectively. The exponential path-loss laws lead to significant variations in signal power at various points in the cell. In this chapter we are concerned with cooperative radio communication that specifically engages one or more of these defining aspects.

Within the context of cellular radio, cooperative communication may be used to enhance capacity, improve reliability, or increase coverage. It may be used in the uplink or the downlink. In the communication between a base station and a mobile, the cooperating entity may be another base station, another mobile, or a dedicated (often stationary) wireless relay node. The cooperating entity may have various amounts of information about the source data and channel state information. Cooperation may happen in the physical layer, data link layer, network layer, transport layer, or even higher layers. The large number of different

ways that cooperation may be exploited to improve the quality of service in cellular radio has given rise to much research and a rich and expanding literature. There are many questions that remain unanswered, among them the relation between the various forms of cooperation and their relative merits are in general not fully known. In this chapter, we aim to catalog some of the directions of research in this area, and outline some of the open questions.

1.2 Base station cooperation

Base station cooperation can take multiple forms. The simplest form of base station cooperation, especially with multiantenna base stations, involves the exchange of information among neighboring cells regarding their cell-edge nodes and remote-cell aware processing at each of the base stations. Then, each of the base stations can put a null on the channel gain vector of the nodes that generate and/or are harmed by the most cochannel interference. This and other simple scenarios like it are in the realm of interference management, and are possible without fully coordinated action from base stations. Specifically, this form of action does not require the base stations to know the traffic for other base stations (therefore the issue of a wideband backbone and its delay does not come into play), nor is it required to know the codebooks used by the other base station, and nor does it require the base stations to be synchronized.

1.2.1 Downlink cooperation

For downlink base station cooperation, base stations can generate a virtual multi-antenna array with zero-forcing beamforming. There are a variety of ways to exploit this general idea. Somekh *et al.* [3] used the circular Wyner cellular model [4] to find expressions for downlink (and uplink) capacities with base station cooperation, which is also sometimes called multicell processing. In [5] the same model and a zero-forcing beamforming approach were used for data transmission in multiple cells. In particular, the approach is to transmit to the best user in each cell, and the high-load asymptotics are derived in an information theoretic approach. Mundarath *et al.* [6] considered the scheduling aspects of distributed downlink zero-forcing beamformers under finite loads.

Such downlink strategies require certain assumptions about sharing of information among cells. To begin with, the data must be shared among the base stations. Secondly, the base station transmitters must be synchronized. Finally, the channel state information of the users must be shared among the base stations, and must be kept up-to-date, so that beamforming vectors can be reliably determined.

The nascent area of distributed beamforming has seen much activity; we briefly mention a representative sample of the results.

The effect of channel state statistics on distributed beamforming was investigated in [7]. Ng *et al.* [8] developed a distributed method of beamforming by message passing between adjacent base stations instead of sharing the data between many base stations.

Mudumbai *et al.* [9] investigated the feasibility of distributed beamforming from the viewpoint of local oscillator phase errors, showing encouraging results. However, the results were tempered by the fact that in this study it was assumed that the frequency of the oscillators is stable. Brown and Poor [10] proposed a method of carrier synchronization for distributed beamforming.

Other works in this area include [11–18]. A tutorial on the challenges and progress in distributed beamforming is given in [19].

There is a key difficulty that limits the usefulness of conventional beamforming techniques in the distributed scenario: because the antennas are not colocated, the difference of propagation delay from different antennas to a node will become a relevant parameter. For beamforming to a single node (single-beam solution) any difference in delays can be absorbed into the beamforming coefficients. Multiple beams may also be generated in the same manner, but only as long as the target nodes are close to each other, i.e., the delay vectors for various nodes must be approximately similar. If the target nodes are far from each other *and* the transmit antennas are also far from each other, then the conventional methods of beamforming may not work.

The degradation of distributed beamforming systems due to the distribution of the antennas and the target nodes is a subject that, to our knowledge, has not been systematically investigated. Also, the design of new optimization techniques to develop beamforming vectors in the presence of different delays remains an open problem.

To study this issue further, it is useful to separate the two difficulties raised by this delay variance. The first one is the induced change in phase, which can be addressed via, e.g., systems of equations that impose the constraints at various nodes. The second, more challenging, problem is due to the variance in the time of arrival of the leading edge of each symbol at various nodes. Assuming that the arrival of symbols from the distributed antennas is calibrated to be cotimed at node A, the leading edge of the symbols may not arrive cotimed at node B.

To our knowledge, no comprehensive method is known to address this problem. Intuitively, if the symbol duration is much larger than the differences in time of arrival, then there is a chance that if the phases can be appropriately adjusted, the overall effect can be brought under control. This also suggests the use of systems with longer symbol duration, e.g., OFDM. It would be interesting to investigate whether variations of techniques used in OFDM, such as cyclic prefix, can be used to “collect” the various components of the distributed beamforming that may be out of phase and out of time.

Aside from the above-mentioned fundamental issue, there are also practical issues that require careful consideration and design. In particular, distributed beamforming requires delicate accounting for various types of delay, not just

in the channel but also within the base station and signal delivery path. Any unaccounted for delay, or delay variation anywhere within the transmit or receive path, would cause transmitted signals to arrive at the mobile station unaligned, causing loss in beamforming gain. These are requirements that often do not appear in theoretical studies, but in fact play an important role in any practical implementation.

To summarize, base station cooperation offers the opportunity for improvement in two opposing directions: incorporating more theoretical results and addressing practical issues. Among various aspects that call for further investigation, one may name:

- possibilities with multiantenna mobiles, among them the extension of results from multiple-input multiple output (MIMO) broadcast channels to the distributed MIMO case;
- the effect of partial channel state information or partially outdated channel state information;
- quantized channel-state feedback for distributed beamforming has been addressed in [16], but there is room for much more work in this area;
- the effect of uneven channel state information across a set of heterogeneous mobiles;
- investigation of limits on the backbone, e.g., limits on sharing of traffic data.

1.2.2 Uplink cooperation

The problem of uplink cooperation is rather different from its downlink counterpart. In the uplink cooperation scenario, a mobile might be in a situation where no single base station can decode its data alone. However, the signals received at two or more base stations may be sufficient to decode the mobile data.

The collection of information at various base stations and their combination present new issues. In particular, since each of the base stations cannot decode the received signal alone, these signals must be sampled and exchanged among base stations, which requires significantly larger bandwidth than the data do. Thus, considering the effect of base station cooperation on the backhaul capacity becomes an important issue. The capacity of the uplink linear cellular networks with base station cooperation via finite capacity links was broached in [20], and bounds on the rate of the system under the Wyner model were obtained from an information theoretic viewpoint. This work generated broad insights into the general capabilities of uplink base station cooperation, but the specifics of coding and signal design for such systems remain open problems.

Thankfully, the uplink does not suffer in quite the same way from the timing problem that plagues the downlink distributed beamforming (see Section 1.2.1). The varying propagation times from the mobiles to base stations can be compensated in the algorithm that combines the data from multiple base stations, since the signal of each of the mobiles can be extracted separately. However, the

problem will remain if we wish to listen to mobile A while simultaneously nulling the interference from mobile B, and these two mobiles have significantly different delay vectors to the set of base stations participating in multicell processing.

The scope for future work in the area of uplink multicell processing is in two directions: incorporation of communication theoretic results into uplink cooperation and addressing issues related to practical limitations. The potential areas of work include:

- practical implications of the restrictions on the backhaul capacity and delay;
- iterative methods based on belief propagation;
- compute-and-forward (hashing) methods to reduce the cooperation bandwidth requirement between the base stations;
- analysis of nonideal conditions, including uncertainties in channel state information;
- the effect of nonideal synchronization and sampling;
- investigating possibilities presented by multiantenna mobiles.

1.3 Dedicated wireless relays

Traditional cellular networks provide fixed throughput for all subscribers where a basic voice service can be supported. Unlike such networks, broadband wireless cellular networks promise a high data rate throughout the coverage area. While such promise is feasible for the inner coverage area, at the cell-edge data rates are limited for various reasons. Decreasing the cell-size is one way to satisfy the required data rate; however, it is a costly solution because it requires the installation of additional base stations. In contrast, deploying relay stations provides a cost-effective solution. Compared with a full-scale base station, a dedicated relay can save on equipment costs, backhaul link, and deployment.

A relay station assists the main base station to improve its coverage or throughput. A relay station can be used to extend the coverage area of a base station, or to provide coverage in so-called holes.¹ In addition, thanks to the advances in antenna array techniques, relays can also be used to improve throughput and capacity.

Due to above facts, the IEEE 802.16 Working Group has developed the IEEE 802.16j standard with techniques that are compatible with the WiMAX standard.

1.3.1 IEEE 802.16j

The IEEE 802.16j standard was created to be backward compatible with the 802.16e standard known as WiMAX. Various modes of operation of 802.16j fit within the WiMAX OFDMA frame. In all the various modes of 802.16j, the base

¹ For example, in tunnels or in certain areas inside a building.

station allocates part of its uplink and downlinks subframes for communicating with the relay station(s). It is envisioned that legacy mobile nodes are able to integrate seamlessly into 802.16j, therefore the mobiles are oblivious to the relays, i.e., they cannot distinguish between the relay and base station.

Two of the modes of operation considered in the IEEE 802.16j standard are transparent and nontransparent modes. The usage of these modes depends on whether it is intended to increase throughput for cell-edge mobile stations, or to extend coverage to the mobile stations unreachable by base station. The transparent mode allows for one-time relaying while the nontransparent mode allows for multiple-time relaying. The transparent mode can be used, e.g., for in-building coverage, while the nontransparent mode can be used to access remote areas which might possibly require multiple relaying. There are also differences within the downlink and uplink frames of these two modes. In transparent mode only the traffic portion is exchanged between relay and mobile stations, while in nontransparent mode in addition to the traffic portion other signals such as synchronization, downlink and uplink maps, and ranging need to be exchanged as well.

Both the transparent and nontransparent modes are multihop modes, i.e., the relay intervenes between the source and destination, and the data portions of source-relay and relay-destination communications are performed separately in time. Another mode of operation in the IEEE 802.16j standard is cooperative relaying, where the base station and relay transmit the same signal, or two copies of the same signal, to the mobile simultaneously. As long as the timing difference between the signal of the base and relay stations as seen by mobile stations is within the acceptable range, the mobile station sees the combined signals as a signal with high diversity.

Operational cooperative relaying has multiple requirements. First, traffic data need to be exchanged between the relay and base stations. Second, the deployment of the relays needs to be such that the time difference seen by the mobile station does not cause OFDMA intersymbol interference. With these practical requirements fulfilled, research efforts have been focused on the various MIMO techniques that can be used to achieve cooperation between base and relay stations. The IEEE 802.16j standard says very little about the techniques for implementing cooperative relaying, therefore there is significant room for innovation by the wireless industry within the context of the standard.

It must be noted that other broadband wireless standards, such as Long-Term Evolution (LTE) and LTE-Advanced, consider the use of relay stations. For details, the readers are referred to Chapters 15 and 16 of this book.

1.3.2 High-spectral-efficiency relay channels

One of the main drawbacks of relaying is that in effect it requires duplicate transmissions (e.g., base station to relay and relay to mobile), unlike standard single-hop transmission. For instance, in both transparent and nontransparent

modes of the IEEE 802.16j there are multiple zones of uplink and downlink subframes that are assigned for the exchange of traffic between base station and relay stations. The loss of time and/or bandwidth is more pronounced for multihop relaying.

However, the advantages of relaying often more than offset the loss of bandwidth. The obvious advantages are the reduction of path loss and shadowing, as well as providing path diversity, but the advantages of relaying go beyond the obvious. For example, both the base station and the relay are stationary (non-moving) and the base station is often elevated, so it is possible to estimate the channel gains between the base station and the relay with a very high degree of accuracy and stability, far beyond what is possible with mobiles. In addition, it is possible to use antenna arrays in both the base station and the relay, which combined with the accurate channel state information leads to a higher spectral efficiency as well as more efficient frequency reuse.

More specifically, the base station can employ space-division multiple access (SDMA) techniques to transmit traffic to several relay stations using the same bandwidth. For efficient implementation of SDMA, the channel state information of each relay must be known by the base station with high precision. In fact, the more precise the channel state information, the larger the number of relay stations that can be served within the same bandwidth. Thanks to the fixed location of relay and base stations, it is possible to obtain a high-quality channel state information of each relay station. Likewise, it is possible to use a similar technique in the uplink to increase uplink spectral efficiency. For instance, collaborative spatial multiplexing, which is also introduced in the IEEE 802.16e and other wireless broadband standards, allows multiple relay stations to transmit uplink traffic utilizing the same burst location, i.e., the same bandwidth. If relay stations are equipped with antenna arrays, other MIMO techniques such as spatial multiplexing can also be used to further enhance spectral efficiency of downlink and uplink.

Improving spectral efficiency of relay channels can further increase the utilization of relays in broadband cellular networks, and therefore is one of the important research topics in this area. For instance, the design of adaptive MIMO precoding techniques that can provide robustness as well as higher throughput can facilitate cellular relays. This could lead to precoding weights that adapt to spatial multiplexing, beamforming, or nulling.

The various costs related to the backhaul channel constitute a big portion of the cost of cellular network deployment, operation, and maintenance. Increased utilization of wireless resources will result in shrinking cell sizes and an increase in the number of base stations, therefore it is expected that backhaul link expenses will be in future broadband networks, generating interest in backhaul links that are cheaper than laying cable or dedicated microwave links. It has been noted that one can use the same family of broadband wireless technologies that are servicing end-users to connect to some base stations. The similarity of operation and use of wireless backhaul links and relaying technologies suggests a potential

unification of these two applications. Thus, spectrally efficient relay channels could eventually also pave the way to less-expensive and easily deployable back-haul links, and might even lead to unified technologies or standards for both.

1.4 Mobile relays

In the previous two sections, we considered the outlook for base station cooperation and dedicated relays. It has been noted that there is nothing *in principle* that precludes the possibility of mobile relays, although technologically their implementation is much more difficult. In this section, we give a brief overview of mobile relays. We begin by considering the distinguishing characteristics of mobile relaying.

One of the fundamental differences between mobile and fixed relays is the limitations on power/energy in the mobile nodes. Fixed relays can be connected to the power grid, while the mobiles are dependent on resident energy storage, which with the present-day technologies is a severe limiting factor. This situation seems a fairly stable one, since neither energy storage devices with orders-of-magnitude higher energy densities, nor an efficient means of tetherless delivery of energy to mobiles, is visible on the technological horizon.

Another distinguishing factor of most mobile nodes, compared to fixed relays, is one of size. Mobile nodes are no more than several centimeters in each dimension, and this puts fundamental restrictions on the number of antennas that can be deployed on a mobile. Polarization diversity antennas offer some improvement, but a fixed relay has much more flexibility in the number of antennas.

An aspect of mobile relaying, which is not unrelated to size and energy, is computational complexity. However, unlike size, this is less of a fundamental limitation. In the past, advances in computational power, measured in MIPS/mm³, have been much more rapid than, e.g., advances in battery technology measured in terms of energy density (joules/mm³). Thus it is not unreasonable to assume that near-future technologies in mobiles will become ever more computationally complex, while the power available to them will grow at a much slower pace.

Due to limited resources, any mobile relay must balance the needs of the node itself with relaying for other nodes. This includes not only power and computation, but also the total spectral efficiency available to a node. The fundamental tradeoff between a node's own communications and relayed bandwidth was addressed in [21], which showed that the competition between its own bandwidth and the relayed bandwidth does not constitute a zero-sum game. However, there will still be questions of the motivation of a relay node to use local resources for other nodes. The specific aspects of network-wide management of resources, and the development of network control algorithms that guide the action of mobile relay nodes that also have individual incoming/outgoing traffic, have attracted some attention but a complete understanding of these algorithms has still not been achieved. Some interesting advances have been made using game theory and pricing analysis. However, a good part of the work in this area is not relevant

to the design of cooperative cellular networks, because the nodes in a cellular network are not autonomous agents and most decisions are, in fact, made in a centralized manner. Resource allocation and network control for mobile cooperative nodes (including aspects such as local rate splitting) are interesting problems that, under the practical conditions that are of interest to the designers of cellular systems, remain for the most part unsolved.

1.5 Conclusion

Cooperative communication is one of the promising wireless technologies that has been reintroduced in the last decade, and it has promising applications in the context of cellular networks. This chapter has presented a brief overview of some of the aspects of research in cooperative cellular networks. To summarize, several important directions of future work seem to beckon wireless researchers. One direction points to the more sophisticated algorithms and harnessing the full power of the coding and signaling methods that are emerging from information theory. Another direction is to refine the models in order to get a more realistic grip on the practical aspects of operation in a cellular network. Finally, most systematic study and analysis of cooperation has concentrated on the physical layer. However, cooperative action at other layers of the communication hierarchy is also possible, but has not been studied quite as much, and this may present a host of opportunities to future wireless engineers.

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