Chapter 7

Cross–Layer Cooperative Beamforming for Wireless Networks

Lun Dong
Drexel University, USA

Athina P. Petropulu
Drexel University, USA

H. Vincent Poor
Princeton University, USA

ABSTRACT

Cooperative beamforming (CB) is a signal transmission technique that enables long-range communications in an energy efficient manner. CB relies on cooperation from a set of distributed network nodes, each carrying a single transmit antenna and acting as elements of a virtual antenna array. By appropriately weighting their transmissions, the cooperating nodes form one or more beams to cooperatively transmit one or more message signals to the desired destinations. In this chapter, a cross-layer framework is presented that brings the CB ideas closer to implementation in a wireless network setting. The process of sharing among the network nodes the information to be beamed is studied and evaluated in terms of its effect on the spectral efficiency of the overall system. Optimal or suboptimal beamforming weights are designed, and queuing analysis is provided to study delay characteristics of source messages.

INTRODUCTION

Beamforming is a signal processing technique for directional signal transmission or reception. It applies to both radio and sound waves, and has been widely used in wireless communications, sonar, radar, medical imaging and other fields. In wireless systems, transmit beamforming involves a set of nodes that are typically elements of an antenna array. The signal to be beamed to a particular destination is made available to all array elements. Each antenna element multiplies the signal by a weight, and then transmits. The weighted signals from all antenna elements are then combined at the destination for further processing (e.g., equalization and symbol recovery). Suppose that N antennas transmit weighted versions of the same signal, each at power P, and the weights are such that all transmissions add up coherently at the destination (i.e., co-phasing). Then the power of the received signal is proportional to $N^2 P$. The received signal-to-noise ratio (SNR) increases proportionally to N^2, whereas the total transmit power increases only proportionally to N. Thus, beamforming can achieve *high energy efficiency*. By adjusting the weights among the various antennas, one is able to control the beampattern, i.e., the distribution of power in space. Thus, beamforming enables space-division multiple access (SDMA), controls interference and increases the reliability of the communication link. There is also receive beamforming, where a set of antenna elements weight the signal that they receive due to one of more sources/targets. The sum of the weighted signals is processed by a central station in order to obtain information about the target or the incoming signal.

Conventional beamformers, usually referred to as switched/fixed-beam antennas, use a fixed set of weights to combine the signals from the antennas and thus can only form a fixed set of beampatterns. A switch then selects the best beampattern, i.e., the one that yields the highest SNR, or signal-to-interference-plus noise ratio (SINR). The main advantage of the switched-beam approach is its simplicity, while its principle drawback is the lack of flexibility. Since the 1980s, there has been enormous interest in adaptive beamformers or smart antennas, in which signals from different antennas are combined by an adaptive algorithm (Compton, 1988). An adaptive beamformer is able to dynamically adapt its beampattern to satisfy various requirements in different scenarios.

Beamforming was initially studied in the context of an antenna array with elements at fixed locations (Godara, 1997; Krim & Viberg, 1996; Litva & Lo, 1996). Beamforming for linear arrays with randomly located antennas has also been studied in (Donvito & Kassam, 1979; Lo, 1964; Steinberg, 1972), where it was shown that with a large number of antennas a good beampattern can be formed with high probability. In all these cases, the signal to be beamed was provided to the antenna elements via a wireline connection. In a more recent work (Ochiai, Mitran, Poor & Tarokh, 2005), cooperative beamforming (also called collaborative or distributed beamforming) using a set of randomly distributed network nodes was proposed. Network nodes, each equipped with a single omni-directional antenna, were shown to be able to form a beam and collaboratively transmit a common signal to a far away destination. Due to the random placement of nodes, the beampattern could only be described in statistical terms. It was shown that, foruniformly distributed nodes over a disk, the directivity can approach. In (Ahmed & Vorobyov, 2008), it was shown that Gaussian distributed nodes can achieve even lower sidelobes than uniformly distributed nodes.

One of the major differences between cooperative beamforming and traditional beamforming with antenna arrays is that in the former the nodes locations are not known and need to be obtained dynamically. Also, since all nodes operate with independent antennas, there are always phase offsets due to

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