Chapter I
Eigencombining:
A Unified Approach to Antenna Array Signal Processing

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ABSTRACT

This chapter unifies the principles and analyses of conventional signal processing algorithms for receive-side smart antennas, and compares their performance and numerical complexity. The chapter starts with a brief look at the traditional single-antenna optimum symbol-detector, continues with analyses of conventional smart antenna algorithms, i.e., statistical beamforming (BF) and maximal-ratio combining (MRC), and culminates with an assessment of their recently-proposed superset known as eigencombining or eigenbeamforming. BF or MRC performance fluctuates with changing propagation conditions, although their numerical complexity remains constant. Maximal-ratio eigencombining (MREC) has been devised to achieve best (i.e., near-MRC) performance for complexity that matches the actual channel conditions. The authors derive MREC outage probability and average error probability expressions applicable for any correlation. Particular cases apply to BF and MRC. These tools and numerical complexity assessments help demonstrate the advantages of MREC versus BF or MRC in realistic scenarios.

INTRODUCTION

General perspective. Andrew Viterbi is credited with famously stating that "spatial processing remains as the most promising, if not the last frontier, in the evolution of multiple access systems" (Roy, 1998, p. 339). Multiple-antenna-transceiver communications systems, also known as single-input multiple-output (SIMO), multiple-input single-output (MISO), or multiple-input multiple-output (MIMO) systems, which exploit the spatial dimension of the radio channel, promise tremendous benefits over the traditional single-input single-output (SISO) transceiver concept, in terms of data rate, subscriber capacity, cell coverage, link quality, transmit power, etc. Such benefits can be achieved with **smart antenna**s, i.e., SIMO, MISO, and MIMO systems that combine baseband signals for optimum performance (Paulraj, Nabar, & Gore, 2005).

Herein, we consider receive smart antennas (i.e., the SIMO case) deployed in noise-limited scenarios with frequency-flat multipath fading (El Zooghby, 2005, Section 3.3) (Jakes, 1974) (Vaughan & Andersen, 2003, Chapter 3), for which the following signal combining techniques have conventionally been proposed:

- ***Statistical beamforming (BF)***, i.e., digitally steering a radio beam along the dominant eigenvector of the correlation matrix of the channel fading gain vector (S. Choi, Choi, Im, & Choi, 2002) (El Zooghby, 2005, Eqn. (5.23), p. 126, Eqns. (5.78–80), p. 148) (Vaughan & Andersen, 2003, Section 9.2.2). BF enhances vs. SISO the *average*, over the fading and noise, signal-to-noise ratio (SNR) by an *array gain* factor that is ultimately proportional to the antenna correlation and is no greater than the number of antenna elements. Since BF requires the estimation of only the projection of the channel gain vector onto the eigenvector mentioned above, it has low numerical complexity. However, BF is effective only for highly-correlated channel gains, i.e., when the intended signal arrives with narrow azimuth angle spread (AS).
- ***Maximal-ratio combining (MRC)***, i.e., maximizing the output SNR *conditioned* on the fading gains (Brennan, 2003; Simon & Alouini, 2000). This SNR is computed by averaging over the noise only, i.e., conditioning on the channel gains. When the intended-signal AS is large enough to significantly reduce antenna correlation, MRC can greatly outperform BF as a result of *diversity gain* and array gain, at the cost of much higher numerical complexity incurred due to channel estimation for each antenna element.

Note that, for fully correlated (i.e., coherent) channel gains, both BF and MRC reduce to the classical notion of “beamforming” whereby a beam is formed towards the intended signal arriving from a discrete direction (Monzingo & Miller, 1980; Trees, 2002; Godara, 2004).

Statistical beamforming and diversity combining principles have traditionally been classified, studied, and applied separately, leading to disparate and limited performance analyses of BF and MRC. Furthermore, since BF and MRC optimize the average SNR and the conditioned SNR, respectively, they have opposing performance-maximizing spatial correlation requirements, as well as significantly different, correlation-independent, numerical complexities (Siriteanu, Blostein, & Millar, 2006; Siriteanu, 2006; Siriteanu & Blostein, 2007). Because correlation varies in practice due to variable AS (Algans, Pedersen, & Mogensen, 2002), BF or MRC performance fluctuates, whereas numerical complexity remains constant. Therefore, MRC can actually waste processing resources and power, whereas BF can often perform poorly (Siriteanu *et al.*, 2006; Siriteanu, 2006; Siriteanu & Blostein, 2007).

Limitations of stand-alone BF or MRC deployments can be overcome by jointly exploiting their principles, under the unifying framework of *eigencombining*. ***Maximal-ratio eigencombining (MREC)*** first applies the Karhunen-Loeve Transform (KLT) with several dominant eigenvectors of the channel correlation matrix to recast the received signal vector in a reduced-dimension space, and then optimally combines the new, uncorrelated, signals (Alouini, Scaglione, & Giannakis, 2000; Brunner, Utschick, & Nossek, 2001; F. A. Dietrich & Utschick, 2003; Jelitto & Fettweis, 2002; Siriteanu & Blostein, 2007). The number of eigenvectors used for the KLT is referred to as the MREC order. Minimum and maximum orders render MREC equivalent with BF and MRC, respectively (Alouini *et al.*, 2000; Dong & Beaulieu, 2002; Siriteanu & Blostein, 2007). The KLT decorrelating effect simplifies the performance analysis for MREC, i.e., also for BF and MRC, over the entire correlation range (Alouini *et al.*, 2000; Dong & Beaulieu, 2002; Siriteanu & Blostein, 2007). Eigengain decorrelation also simplifies fading factor estimation and combining implementation over MRC, thus reducing the numerical complexity (Alouini *et al.*, 2000; Siriteanu & Blostein, 2007). For the medium-to-high correlation values (i.e., 0.5 – 0.9) often incurred at base-stations in typical urban scenarios (Siriteanu & Blostein, 2007), MREC can reduce problem dimension vs. MRC, further reducing numerical complexity, while offering near-optimum performance, and thus outperforming BF. Consequently, MREC of order selected to suit the channel and noise statistics or the system load can improve signal processing efficiency over BF and MRC (Siriteanu *et al.*, 2006; Siriteanu, 2006; Siriteanu & Blostein, 2007).

Chapter outline and objectives. The next subsection provides more background information on BF, MRC, and MREC. Then, a signal model is described that incorporates additive noise as well as spatial fading caused by signal arrival with AS, for a base station in typical urban scenarios. The traditional SISO approach is then described, and expressions for symbol-detection performance measures such as the outage probability (OP) and average error probability (AEP) are derived. The conventional antenna array signal processing concepts of BF and MRC are studied afterward, for ideal and adverse fading correlation conditions, and their numerical complexities are compared for actual implementations, which require channel estimation. Next, the BF and MRC principles are unified under the framework of MREC, which is shown to simplify the MRC analysis for channel correlation conditions that render difficult direct MRC study. AEP and OP expressions that are derived for MREC but also cover SISO, BF, and MRC, as well as numerical complexity evaluations, serve to demonstrate the benefits of adaptive-eigencombining-based smarter antennas for realistic scenarios with random AS.

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