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A comparative study of heuristic algorithms: GA and UMDA in spatially multiplexed communication systems

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ABSTRACT

A performance comparison of genetic algorithm (GA) and the univariate marginal distribution algorithm (UMDA) as decoders in multiple input multiple output (MIMO) communication system is presented in this paper. While the optimal maximum likelihood (ML) decoder using an exhaustive search method is prohibitively complex, simulation results show that the GA and UMDA optimized MIMO detection algorithms result in near optimal bit error rate (BER) performance with significantly reduced computational complexity. The results also suggest that the heuristic based MIMO detection outperforms the vertical bell labs layered space time (VBLAST) detector without severely increasing the detection complexity. The performance of UMDA is found to be superior to that of GA in terms of computational complexity and the BER performance.

1. Introduction

Recent advances in wireless communication lead to the multiple input multiple output (MIMO) communication systems employing simultaneous use of antenna arrays at both the transmitter and the receiver (Barbarossa, 2005; Tse and Viswanath, 2005). The MIMO architecture exploits multipath propagation to improve the link capacity by establishing multiple parallel channels operating simultaneously in the same frequency band and at the same transmitted power. In contrast to the logarithmic bandwidth efficiency growth obtained with single antenna systems, the capacity growth for MIMO systems is linearly related with the number of antennas. An information theoretic analysis on the capacity of MIMO systems was presented in Telatar (1999) assuming flat, quasi-static and spatially independent Rayleigh fading environment with known channel state information at the receiver. The study concluded that the capacity of multiple antenna channels increases linearly with the smaller of the number of transmit and the receive antennas.

The received signal at a particular receive antenna of a MIMO system is a superimposed representation of the signals transmitted from the multiple transmit antennas. If the MIMO system has N transmit antennas and uses a signal constellation $\mathcal{X}$ of size $B=2^b$ for b bits per symbol, the exhaustive search by maximum likelihood (ML) detection has a computational complexity $\mathcal{O}(B^N)$; hard to implement when B and N are large. Various linear and non-linear suboptimal MIMO detectors are proposed and are well documented in the literature such as zero-forcing (ZF) (Schneider, 1979), minimum mean square error (MMSE) (Honig et al., 1995) and vertical bell labs space time (VBLAST) detector (Golden et al., 1999). These schemes are computationally less expensive but with fairly degraded performance as compared to the ML decoder. The sphere decoder (SD) that searches for optimum solution in the vicinity of the received signal vector is discussed in Fincke and Pohst (1985), Damen et al. (2000), Hochwald and Brink (2003). The average complexity of the SD in general is exponential in the problem dimensions N, but could be dominated by the polynomial terms when N is small and the corresponding signal to noise ratio (SNR) is chosen sufficiently large (Hassibi and Vikalo, 2005).

A performance comparison between two classes of search algorithms namely the evolutionary algorithms (EAs) and the estimation of distribution algorithms (EDAs) is provided in this paper. The algorithms are applied to improve the performance of non-linear MIMO detectors without significantly increasing the computational complexity. EAs are one of the most successful meta-heuristic techniques for solving optimization problems taking their inspiration from natural selection and survival of fittest in the biological world. Genetic algorithm (GA) is one important member of this class of optimization algorithms that will be applied to decode the composite received signal in a MIMO system. GA operates on an initially generated subset of the search

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space and subsequently weeds out the poor solutions based on competitive selection. The population size should be carefully selected because it directly effects the computation time and the optimality achieved. This is followed by the processes of recombination and mutation to generate a new set of probable solutions (offspring) replacing the discarded poor parents. The new set of offspring is biased and directs the search mechanism towards the regions of the search space for which good solutions are already observed. This improves the quality of the output generated after each iteration of the search method. While searching for the optimal solution in time sensitive applications the EAs are desired to achieve satisfactory performance within a reduced number of iterations.

Unlike EAs the EDAs do not use crossover or mutation operators, considered primary tools for GA based optimization. Instead, EDAs explicitly extract global statistical information from the selected solutions and subsequently build a probability model of promising solutions based on the extracted information. New solutions are sampled from the model thus built. In this paper univariate marginal distribution algorithm (UMDA) from the family of EDAs is chosen and the performance of the algorithm is analyzed as a MIMO decoder. A comparison of the BER performance of UMDA with the BER performance of GA is also provided in the simulation results.

The rest of the paper is organized as follows. Section 2 provides the spatial multiplexed system model and sets-up the MIMO detection problem for flat, quasi-static and spatially independent Rayleigh fading environment. A brief overview of existing MIMO detectors is given in Section 3. Sections 4 and 5 detail the MIMO detection based on GA and UMDA, respectively. BER performance analysis of the proposed detectors is discussed in Section 6 followed by the conclusion.

2. The system model

We consider an $M \times N$ MIMO channel (i.e. there are N transmit antennas and $M \geq N$ receive antennas), and a spatial multiplexing system such as VBLAST (Foschini, 1996). At each time instant, the linear baseband system model as shown in Fig. 1 is given by

$$\mathrm{y} = \mathrm{Hx} + \eta \tag{1}$$

with the data vector $\mathrm{x} = [x_1, \ldots, x_N]^{\mathrm{T}} \in \mathbb{C}^N$, the $M \times N$ channel matrix H and $\mathrm{y} = [y_1, \ldots, y_M]^{\mathrm{T}} \in \mathbb{C}^M$ represents the received signal vector. The additive white Gaussian noise (AWGN) is represented by $\eta \in \mathbb{C}^M$ having circularly symmetric complex Gaussian components. The data symbols $x_n \in \mathrm{x}$ are assumed to be zero mean and white with variance σ_x. The noise components $\eta_m \in \eta$ are independent and circularly symmetric complex Gaussian random variables with variance σ_η. Each element of x is determined from the same set $\mathcal{X}$ composed of $B = 2^b$ constellation points where b is the number of bits per symbol. The channel matrix coefficients are i.i.d. Rayleigh random variables h_{mn} representing the channel between the n th transmit antenna and the m th receive antenna. The receiver is assumed to have full knowledge of the channel coefficients. This is a reasonable assumption when the fading is slow enough to allow estimation of the channel state information with negligible error, as in the case of fixed wireless systems.

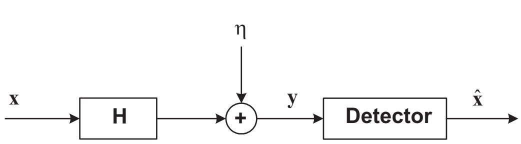

Fig. 1. Linear MIMO system model.

3. Review of MIMO detection schemes

Major suboptimal detection schemes for spatial multiplexing systems include linear equalization followed by quantization and nulling and canceling (or decision feed back) detection (Foschini, 1996). In linear equalization based schemes, the detected data vector is $\hat{\mathrm{x}} = \mathcal{Q}\{\mathrm{r}\}$ with $\mathrm{r} = \mathrm{Gy}$, where $\mathcal{Q}\{\cdot\}$ denotes component wise quantization according to the symbol alphabet. The ZF equalizer is given by $\mathrm{G} = (\mathrm{H}^H\mathrm{H})^{-1}\mathrm{H}^H$ (H has full rank and H^H represents the Hermitian transpose of the matrix H), while the MMSE equalizer is given by $\mathrm{G} = (\mathrm{H}^H\mathrm{H} + (\sigma_n^2/\sigma_x^2))^{-1}\mathrm{H}^H$ (Kay, 1993). In contrast to the linear equalization schemes where all the layers are detected jointly the nulling and canceling also known as VBLAST decoder uses a serial decision feedback approach to detect each layer separately. The VBLAST decoder is initialized by the output of the ZF or the MMSE approach; the corresponding detectors are referred to as VBLAST-ZF and VBLAST-MMSE, respectively.

Finally, the ML detection yields minimum error probability for equally likely data vectors. The ML detector is given by

$$\hat{\mathrm{x}} = \arg\min_{\mathrm{x} \in \mathcal{X}^N} \|\mathrm{y} - \mathrm{Hx}\|^2 \tag{2}$$

with $\mathcal{X}^N$ represents the set of all possible symbol vectors. The output of Eq. (2) depends on the minimum Euclidean distance of the M dimensional received signal vector y from $\mathcal{X}^N$ in an N dimensional space. It is evident that the computational complexity of ML decoder grows exponentially with the number of transmit antennas N and the number of bits per transmitted symbol b.

4. GA based detection for MIMO systems

GA is an inspiration based on the principles of natural genetics and selection. The algorithm starts by defining optimization variables, optimization cost and the cost function. Convergence/fitness test follows various components of the algorithm as shown in Fig. 2. All the probable solutions of a problem are encoded in bit level to simplify the following GA recombination operations. In MIMO detection $\forall \mathrm{x} \in \mathcal{X}^N$ that form the ML search space are coded as binary strings called *chromosomes*. Each chromosome is a combination of the probable constellation symbols transmitted by the MIMO transmitter. GA is initialized by randomly generating a

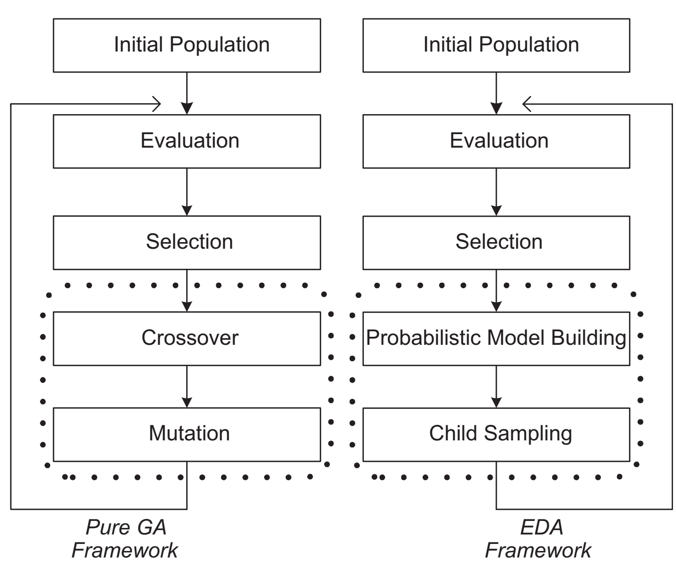

Fig. 2. The flow diagram for GA and UMDA.