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Three Natural Computation methods for joint channel estimation and symbol detection in multiuser communications

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ABSTRACT

This paper studies three of the most important optimization algorithms belonging to Natural Computation (NC): genetic algorithm (GA), tabu search (TS) and simulated quenching (SQ). A concise overview of these methods, including their fundamentals, drawbacks and comparison, is described in the first half of the paper. Our work is particularized and focused on a specific application: joint channel estimation and symbol detection in a Direct-Sequence/Code-Division Multiple-Access (DS/CDMA) multiuser communications scenario; therefore, its channel model is described and the three methods are explained and particularized for solving this. Important issues such as suboptimal convergence, cycling search or control of the population diversity have deserved special attention. Several numerical simulations analyze the performance of these three methods, showing, as well, comparative results with well-known classical algorithms such as the Minimum Mean Square Error estimator (MMSE), the Matched Filter (MF) or Radial Basis Function (RBF)-based detection schemes. As a consequence, the three proposed methods would allow transmission at higher data rates over channels under more severe fading and interference conditions. Simulations show that our proposals require less computational load in most cases. For instance, the proposed GA saves about 73% of time with respect to the standard GA. Besides, when the number of active users doubles from 10 to 20, the complexity of the proposed GA increases by a factor of 8.33, in contrast to 32 for the optimum maximum likelihood detector. The load of TS and SQ is around 15–25% higher than that of the proposed GA.

1. Introduction

Natural Computation-based methods (NCMs, in the following) have been extensively studied during last decades. Since the seminar work of Holland [1], many scientists have studied conceptually, heuristically and quantitatively a wide range of algorithms. Nowadays, there exist many families or branches of NCMs. Frequently, many methods cannot be uniquely assigned to a single class of NCM since they gather interesting properties proper of several different procedures. On the other hand, many applications of these methods have been described in technical literature: communications, control, image processing or electronics, just to name a few. Theoretical descriptions of these algorithms, and even the comparative study and the application of one (most often) or a couple of them to a specific problem, have been studied in many articles (see [2] for instance). Our main aim focuses on comparatively describe the application of three different NCMs in fair terms: Genetic algorithm (GA), Tabu search (TS) and Simulated Quenching (SQ) when applied to a key communications problem, multiuser detection (MUD) in a digital communication channel, where a mobile digital radio channel is shared by U users who simultaneously transmit digital symbols belonging to an M-ary symbol source alphabet.

The task of choosing the different methods to be compared is an open issue, since there exist many possibilities as previously mentioned. We have chosen three classical and well-known methods (GAs, TS and SQ) so that comparisons with other papers can be made easier.

Let us briefly describe these methods. SQ belongs to the branch of Simulated Annealing (SA) related methods. SA is a common algorithm for approaching complex optimization tasks. It was first proposed in [3] and [4], and it has been successfully used for solving several technical problems. The original SA scheme is a generalization of the local search algorithm, where in each iteration of the algorithm a neighbour of each current solution is selected randomly. The new potential solution will replace the current one if cost remains equal or decreases. Its main drawbacks are: (i) possibility of convergence to suboptimal solutions, and (ii) large

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processing time that leads to too slow implementations. SQ reduces computational load by decreasing a parameter called *system temperature*, though, in the process, the convergence to the global optimum is notably limited [5]. Besides, the proposed SQ method, selectively allows some jumps to potential solutions with a higher cost in accordance to the Metropolis rule [6]. However, [7] points out that the main handicap they found was to avoid local minima (by a misplaced transition). This problem can be efficiently addressed with another NCM: GAs. These strategies constitute an efficient alternative for solving highly nonlinear optimization problems since they successfully use exploitative and explorative search in order to avoid local convergence. The particularities of the GA presented in this work are, principally: a reduced computational load, the ability of convergence to quasi-optimal solutions, and the on-line fine-tuning of the genetic operators depending on the diversity of the population, which is quantified using the Shannon entropy. This strategy leads to a robust and flexible algorithm in accordance to the philosophy of GAs.

We have chosen the multiuser detector in DS/CDMA communications as our problem of interest since it is a well-known and widely studied problem, making easier the comparisons with other standard and deterministic receivers. In fact, DS/CDMA is used in communications systems such as IS-95, CDMA2000, FOMA, UMTS, LTE (4G) and is expected to be used also in 5G at least in combination with other techniques, in WiFi data transmission and in some GPS systems.

As interesting previous approaches of NCMs to solve the MUD problem, we can cite the following: a multiuser detector based on a GA was presented in [8]. The scenario is a synchronous DS/CDMA scheme and the algorithm demands good initial estimates of the transmitted data symbols. The asynchronous case was studied in [9], where the interference of the surrounding bits of the remaining users is considered. This GA estimates both the desired bits as well as the edge bits. In 2000, [10] used an algorithm of local search before executing the GA; the performance was close to the single-user limit. The work by Ergun et al. incorporates a multistage detector as a segment of the GA-based detector for improving the convergence rate [11]. More recent approaches include [12,13], that consider a GA-based MUD in frequency selective Rayleigh fading channels, and the method proposed in [14], that studies the properties of a multiuser detector in terms of probability of error and near-far effect resistance. On the other hand, the channel response estimation is specifically addressed in [15], and more computationally efficient algorithms are proposed, for instance, in [16], where a redundancy saving strategy is suggested. Other interesting recent approaches for multiuser detection with GAs include [17–23]. Several earlier references are cited in [24]. In the last decade, tabu search methods for MUD problems have been proposed in [25–27] or in [28], which proposes a user selection scheme for MIMO-CDMA systems. Relevant SQ-SA strategies for MUD have been proposed in [27,29–31], the later is an GA-SA hybrid proposal, while in [30] an SA algorithm is proposed for solving the MUD problem in CDMA, considering both the synchronous and asynchronous cases.

The remaining of the paper is structured as follows:

- Section 2 is devoted to the description of the application problem: joint channel estimation and symbol detection in digital synchronous multiuser communications. Since this is a crucial and well-known problem, it allows to analyze the performance of the proposed NCMs, not only in a comparative analysis among them, but also in contrast to several traditional methods.
- Section 3 presents the basic principles of the NCMs, mainly GA, TS and SQ. In order to facilitate comparison, concise comments to simulated annealing (SA) are outlined, as well. For the sake of brevity, and in order to make the paper more readable, TS and SQ will be explained more concisely, only detailing the main differences with respect to the GA case. Each subsection also shows the specific implementations for the multiuser detection application.
- Finally, Section 4 describes the numerical results, underlining the comparison between GA, TS and SQ in fair terms: their drawbacks and advantages are here explained. For the sake of comparison, some traditional detectors – matched filter, correlator, Radial Basis Function (RBF) networks – have also been included here since these methods have been frequently used in papers approaching this problem, thus allowing an easy comparison with many existing MUD methods.

2. Multiuser detection for DS/CDMA communications

2.1. Problem description

During the last two decades, wireless communications have shown large growth rates per year in several countries. DS/CDMA has been widely studied as telecommunication companies wish to exploit to the maximum the available frequency bands [32,33]. Since DS/CDMA offers high transmission rates, intersymbol interference (ISI) effects become notable and, considered simultaneously with multi-access interference (MAI), they constitute the two most important handicaps to system specifications [32]. If these interferences are not properly controlled, they can lead to drastic degradation of reception quality. Several strategies have been analyzed in order to minimize these interferences, such as power control and optimization of the users' codewords. Traditional schemes relying on a bank of matched filters lead to good performance only when all received codewords are orthogonal. However, real systems rarely present this property and their behaviour is degraded. This degradation becomes more significant if the scenario presents near-far effects. Verdú showed that this drawback was solved if all the users data sequences were jointly-extracted [33]. However, the complexity of this optimum detector based on the maximum likelihood criterion increases exponentially with the number of active users. As a consequence, suboptimal detectors have been widely developed. A considerable amount of these procedures uses Natural Computation methods as previously mentioned in Section 1.

2.2. Description of the DS/CDMA scenario

The following discrete-time signal and channel model has been considered: a BPSK (Binary Phase Shift Keying) communication system with U active users, each of them using a normalized modulation codeword from set $\{s_i(t)\}_{i=1}^{U}$, and transmitting through a flat-fading frequency-nonselective Rayleigh channel, with a zero-mean white Gaussian noise. Perfect synchronization of all signals is assumed. Suppose that the ith user of the system transmits a sequence $d_i(n)$ of F (frame duration) statistically-independent symbols that modulates waveform $s_i(t)$, with the result that the spectrum width is spread by a factor N (known as *processing gain*). Consequently, the signal transmitted by user i is

$$x_i(t) = \sum_{n=0}^{F-1} d_i(n) s_i(t - nT) \tag{1}$$

where T is the data symbol period, $d_i(n)$ are the users' data symbols, and the codewords waveforms are generated as

$$s_i(t) = \sum_{\ell=0}^{N-1} s_{i,\ell}\, \psi(t - \ell T_c) \tag{2}$$

where $s_i = (s_{i,0}, \ldots, s_{i,N-1})^T$ represents the codeword of the ith user, $T_c = T/N$ is the chip period and $\psi(t)$ denotes a chip pulse of