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Multi-objective and constrained optimization for DS-CDMA code design based on the clonal selection principle

Sanjoy Das *, Balasubramaniam Natarajan, Daniel Stevens, Praveen Koduru

Department of Electrical & Computer Engineering, Kansas State University, Manhattan, KS 66506, United States

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Abstract

This paper proposes two new algorithms based on the clonal selection principle for the design of spreading codes for DS-CDMA. The first algorithm follows a multi-objective approach, generating complex spreading codes with ''good'' auto as well as cross-correlation properties. It also enables spreading code design with no restrictions on the number of users or code length. The algorithm maintains a repertoire of codes that are subject to cloning and undergo a process of affinity maturation to obtain better codes. Results indicate that the produced code sets lie very close to the theoretical Pareto front. A second penalty function-based constrained optimization algorithm based on clonal selection is proposed. It is applied to the design of spreading codes with pre-defined power spectral density requirement. The results suggest that the algorithm is capable of lowering significantly, the power spectra at undesired frequencies. Therefore, with the proposed algorithm, a DS-CDMA transmitter can, for the first time, selectively transmit power across the transmission bandwidth and adjust to jammers and other interferers. This study illustrates that using two stages of multi-objective and constrained optimization, using the proposed clonal selection algorithms, is an effective code design strategy.

Keywords: Clonal selection; Multi-objective optimization; Artificial immune systems; Wireless communication; CDMA

1. Introduction

1.1. DS-CDMA code design

We are currently experiencing a rapid proliferation of wireless communication systems and devices in our daily life. These systems and devices share the wireless channel by employing smart *multiple access* techniques. Direct-sequence code division multiple access (DS-CDMA) [32] is one of the most popular multiple access techniques and is the technology driving the third generation cellular as well as the wireless local area network (WLAN) market. In a DS-CDMA based wireless network, multiple users transmit their information (digitized voice or data) signals simultaneously over the same frequency [25]. However, each user is assigned a specific spreading code, which serves as the ID for that user. An analogy to DS-CDMA could be that of being at a cocktail party with two humans and two aliens. The humans and aliens talk at the same time and over the same frequency, but the language used by humans is different from that of the aliens. This makes the human communication undetectable to the aliens and vice-versa. Here the language becomes the code.

The choice of the spreading code plays a significant role in the quality of service experienced by the user. The correlation properties of the spreading codes directly impact the amount of interference introduced by competing users in a multi-user environment [30]. This can be thought of as the effect of increasing the number of humans in the cocktail party. As more people begin talking, the less distinguishable a certain person will become. This multiple access interference (MAI) reduces the practical channel capacity and leads to reduced performance as a result of increased noise levels. In an asynchronous DS-CDMA system, this MAI can be combated using efficient spreading codes with ''good'' cross-correlation (CC) properties [18]. It is important to note that since many users may be operating in the DS-CDMA system at any time, the CC properties of all sequences in the set should be considered when determining the average performance. The auto-correlation (AC) properties of a set of codes are also important [32]. Specifically, the AC properties control the spectral properties of the transmitted signal and play a key role in synchronization at the receiver end. As with CC, the search for codes with ''good''

* Corresponding author.
E-mail address: sdas@ksu.edu (S. Das).

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AC properties should consider the average AC properties of a code set.

The design of spreading codes has been widely studied, and several methods for generating code sets with good AC and CC properties have been proposed [15,19,27–29,33,34]. Unfortunately, the prior works provide binary or complex spreading codes that have restrictions on the code length N (i.e., N is limited to 2^n or $2^n \pm 1$, where $n \in I$, or N is prime). Furthermore, there is also a restriction on the number of users, K, e.g., Walsh–Hadamard codes consider code sets with $K = N$, while in Gold codes, $K = N + 2$. Finally, deterministic/parametric methods of code design result in codes with well-defined correlation structure that cannot be altered. While, this design framework is adequate for second and third generation wireless systems, future wireless systems (e.g., software defined radio [26], cognitive radio [13]) require more flexibility in code length, capacity as well as correlation properties. Additionally, in order for wideband DS-CDMA systems to co-exist with other standards and also perform well under jamming and intentional interferers, it is important that we have the ability to control the transmitted power in specific frequency sub-bands [20]. However, in current DS-CDMA architecture, power control schemes merely increase or decrease transmitted power in the entire bandwidth and *frequency selective* power control (FSPC) has never been implemented or explored. Given these serious drawbacks of current code design frameworks, a new design approach is needed to meet the challenges of next generation systems.

An evolutionary approach to flexible code design has been studied recently in refs. [1,22]. The genetic algorithm has been applied to obtain codes of length $N = 16$, 32, and 64. It is applicable to both discrete and continuous phase angles. In all cases, the algorithm is shown to converge to the theoretical limit. While yielding optimal codes with a wide range of correlation properties, unfortunately, it also suffers from slower convergence. A state of the art multi-objective evolutionary algorithm NSGA-II [7] is also implemented. Although NSGA-II is popular with many multi-objective applications, when designing good code sets with good CC and AC properties, the fitness landscape is quite rugged. Simulations of NSGA-II reported here shows that it is ineffective in the present problem. In this paper, a clonal selection based algorithm for the optimization of direct-sequence code division multiple access (DS-CDMA) spreading codes are proposed. The proposed approach allows both, flexible code design with a wide range of correlation and/or spectral properties while placing no restriction on the code length N, or the number of codes K, as well as for frequency selective power control. The convergence of the proposed algorithm is also much better than the genetic algorithm approach presented in ref. [1].

1.2. The clonal selection algorithm

Clonal selection is a central feature of the vertebrate immune system [8]. The immune system's primary function is to respond and eliminate foreign molecules known as antigens. In order to do so, this system makes use of white blood cells, including the B-cells to recognize antigens. Following the pattern recognition step, the immune system then initiates an adaptive response mechanism to cull out the invading antigens by means of producing antibodies. Each B cell is linked with a single antibody. The ability of the antibodies to recognize and respond to an antigen is known as its affinity. A cell that is more capable of recognizing and subsequently removing a given antigen has a higher affinity than others. Such an antibody receives more stimulation to proliferate the immune system by a mechanism called cloning [6,8–11]. Cloning is a mitotic process that produces exact copies of the parent cells. The clone is then subject to a process called affinity maturation. Affinity maturation ensures that the affinity of each cell is improved to allow the speedy removal of the foreign antigens. Within affinity maturation, the cell undergoes a high rate of mutation called hypermutation. In a bid to increase its affinity, a cell that has a lower affinity has a higher probability of mutation. Following the affinity maturation process, cells undergo selection. Those with affinities lower than a certain threshold are removed from the immune system. The entire process of clonal selection looks like an accelerated form of Darwinian evolution in a microcosm. It is repeated until the organism acquires immunity to the foreign antigens. An overview of this process is shown in Fig. 1.

Algorithms for optimization, modeled after the clonal selection process, have been proposed recently, including an application to multi-user detection in CDMA [16]. These algorithms maintain a large population/repertoire of solutions and are not unlike genetic algorithms. The individual solutions within the repertoire correspond to antibodies. Better solutions are assigned higher affinities. The individuals undergo affinity maturation, and those with higher affinities are merged with the repertoire. An algorithm by de Castro and von Zuben, CLONALG (CLONal selection ALGorithm) [9] offers a versatile algorithm for learning as well as stochastic optimization. CLONALG provides the necessary theoretical backdrop for the proposed algorithm, although the present research addresses a multi-objective problem.

1.3. Multi-objective and constraint handling optimization approaches

When dealing with optimization problems involving multiple objectives, the conventional concept of optimality does not

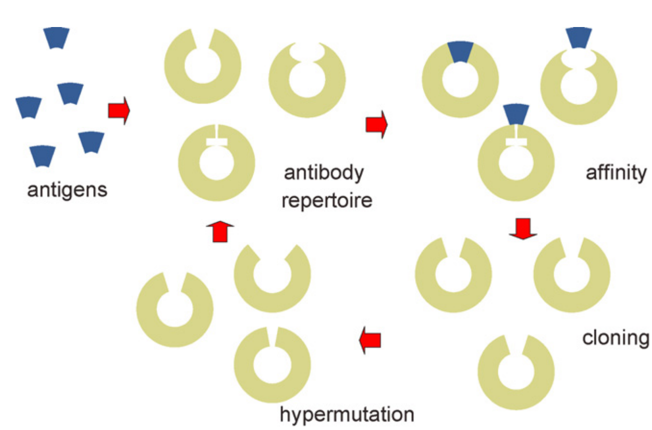

Fig. 1. A schematic of the clonal selection process.