Evolution of Digital Modulation Schemes for Radio Systems

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ABSTRACT

We apply an evolutionary strategies (ES) algorithm to the problem of designing modulation schemes used in wireless communication systems. The ES is used to optimize the digital symbol to analog signal mapping, called a constellation. Typical human-designed constellations are compared to the constellations produced by our algorithms in a simulated radio environment with noise and multipath, in terms of bit error rate. We conclude that the algorithm, with diversity maintenance, find solutions that equal or outperform conventional ones in a given radio channel model, especially for those with higher number of symbols in the constellation (arity).

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*; I.2.8 [**Artificial Intelligence**]: Problem Solving, Control Methods, and Search—*Heuristic methods*

Keywords

Constellation, Cognitive Radio, Adaptive Modulation, Evolutionary Algorithm

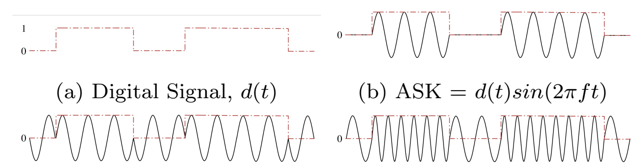
1. INTRODUCTION AND BACKGROUND

Software-defined radio (SDR) allows for radio transmission parameters, such as frequency, bandwidth, transmit power and more to be changed on the fly purely in software. We can conceivably build a system which allows a cognitive algorithm to optimize the modulation scheme given a set of channel conditions. Designing an optimized modulation scheme, however, is a prohibitively complex mathematical problem. We investigate the use of evolutionary algorithms to intelligently create and adapt the modulation scheme based on a set radio environment.

GECCO'14, July 12–16, 2014, Vancouver, BC, Canada.
ACM 978-1-4503-2881-4/14/07.
http://dx.doi.org/10.1145/2598394.2598449.

1.1 Modulation Schemes and Constellations

In order for digital data to be sent via radio, it must be converted from digital to analog airwaves and back. The digital data on the input side of the transmitter must first be divided into blocks of bits and these mapped to waveforms, in a process called modulation. Modulation consists of varying some property or properties of a periodic waveform to carry information. The three primary categories of modulation schemes are those that vary the amplitude, frequency, and phase properties [4]. Basic examples of these modulation schemes can be seen in Figure 1.



(a) Digital Signal, $d(t)$ (b) ASK $= d(t)sin(2\pi ft)$

(c) PSK $= \begin{cases} sin(2\pi ft), & 1 \\ sin(2\pi ft + \pi), & 0 \end{cases}$ (d) FSK $= \begin{cases} sin(2\pi f_1 t), & 1 \\ sin(2\pi f_2 t), & 0 \end{cases}$

Figure 1: Modulation schemes and their equations. Digital signal $d(t)$ is modulated by amplitude (ASK), phase (PSK), and frequency (FSK).

A visual way to represent a modulation scheme is its constellation in IQ space. We plot each modified cosine as a point the X (in-phase) and Y (quadrature) axes. In this space, distance from the origin represents the ratio of amplitude and angle represents phase shift, from the original cosine. Figure 2 depicts a modulation scheme where the 8 digital symbols are mapped to 8 waveforms which vary only by phase.

The number of symbols defined in the modulation's constellation is called the arity. The number of bits which can be represented per symbol in a constellation is equal to $log_2(arity)$. Thus, more defined symbols mean a higher data rate, but make each symbol more difficult to resolve in the presence of noise, resulting in error; the placement of points should be optimized to improve resolution ability.

2. ALGORITHMS

Since the constellation space is intrinsically a real-valued search space, evolution strategies was a natural choice of algorithm. A canonical ES was implemented with (μ, λ) survival selection, elitism, and Gaussian perturbation as a mutation operator, the σ of which is mutated per individ-

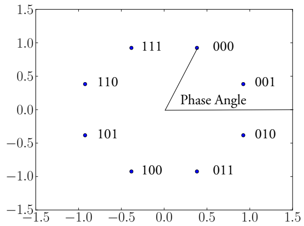


Figure 2: An Arity 8 PSK Constellation

ual. We use a learning rate of $\tau = 1/\sqrt{gen}$, mutating the σ as $\sigma\prime = \sigma * N(0, \tau)$. In addition, global intermediary recombination is used to generate children. Having found that the ES would converge prematurely on constellations with higher arity, we implemented two methods of maintaining diversity—the Age-Layered Population Structure based the original ES [3] and the island model [2].

3. EXPERIMENTS

3.1 Simulation

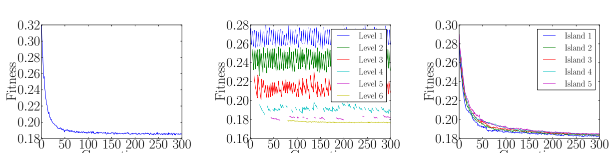
The GNU Radio open-source project was chosen as the simulation tool [1]. The simulation encodes a random stream of bytes using a generated constellation, simulates Gaussian noise and multi-path, then decodes this signal. This output stream is then compared to the input, and the bit error rate (BER) is calculated over 10,000 bytes. This value is used as our minimized fitness function, between 0 and 1. Due to the software used, the simulation itself is stochastic, with a standard deviation of about 1%.

In order to prevent the search algorithms from simply increasing transmit power, we normalize the points such that the average norm of the constellation is 1.

3.2 Experimental Results

We compare constellations generated by our algorithms, after 150 generations, to canonical constellations for arities of 4, 8, and 16—QPSK, 8PSK, and 16-QAM, respectively, averaged over 10 runs each. For arity 4, our algorithms generated what is essentially the QPSK constellation. For arity 8, the generated constellations were different in topology but not a huge improvement over 8PSK. Results are summarized in Table 2.

While easy to modulate and demodulate, it is recognized that the rectangular 16-QAM constellation is not the ideal configuration for order 16 (or higher)[5]. However, the discovery of new constellations has been limited by the difficulty in theoretically computing their error rate.



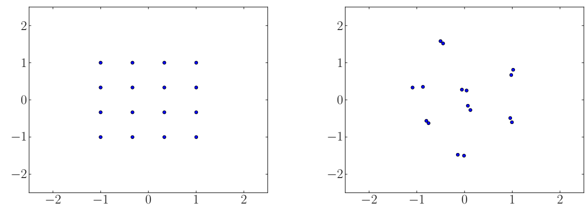
(a) Basic ES (b) ALPS ES (c) Island ES

Figure 3: Best Fitness vs Generation for Each Algorithm, Arity 16

Table 1: Results of Arity 16 Runs

Algorithm	Mean BER	% Decrease[1]	p-value[2]
16-QAM	0.314	N/A	N/A
Basic ES	0.184	41.6	5.93e-12
ALPS ES	0.174	44.8	2.72e-20
Island ES	0.179	43.0	5.93e-12

[1] versus 16-QAM
[2] type 3, 1 tailed t-test



(a) Canonical 16-QAM (b) Generated Constellation

Figure 4: Individuals, Arity 16

We had to extended the number of generations to 300 in order to see convergence in at least two of the algorithms. We see much greater gains at arity 16, showing that the evolutionary approach has promise in developing new modulation schemes.

Table 2: Best Fitness (BER) Produced by Each Algorithm

Arity	Canonical	Basic ES	ALPS ES	Island ES
4	0.0783	0.0753	0.0728	0.0745
8	0.189	0.177	0.174	0.178
16	0.314	0.180	0.174	0.179

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