Optimization of the Phase-Stability Devices with Different States by the Grey Wolf Optimization Method

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Abstract – **In the context of modern communication engineering, an important direction of circuit design is the development of electrically controllable attenuators and adjustable amplifiers capable of varying the signal amplitude in systems with different steady states. To ensure the quality of signal transmission in communication systems, it is critical to minimize the effect of parasitic reactive elements on the phase shift in the gain control. It is evident that the optimization methods that have been developed for such devices frequently result in physically unfeasible solutions. This phenomenon can be attributed to the multi-extremality of the target function. In this study, a multi-criteria optimization of phase-invariant devices is carried out using a bioinspired Grey Wolf Optimization (GWO) method, which demonstrates high efficiency in finding optimal solutions.**

Keywords – **phase stability, multi-criteria optimization, voltage-controlled attenuator, grey wolf optimizer, group time delay, phase shift**

I. INTRODUCTION

Contemporary electronic systems, including fifth generation communication (5G), satellite navigation, and radar systems, necessitate greater flexibility and precision in signal processing [1–2]. This requirement presents complicated obstacles for developers focused on optimizing signal performance through amplitude and phase manipulation, as well as switching mechanisms [3–5]. Key elements in addressing these challenges include voltage-controlled attenuators (VCA), phase shifters, modulators, adjustable amplifiers, and controlled filters. These devices are characterized by both fixed and variable parameters, with the variable parameters influencing the system's state while remaining constant during intended signal processing [6–7].

Optimizing these parameters represents a complex multicriteria problem [8]. Existing methods, including the method of fastest descent, Newton's method and simulated annealing, apply to specific system classes but do not universally ensure a global optimum. Additionally, their effectiveness heavily depends on the initial parameters and may require significant computational resources. Therefore, developing a new, more efficient optimization method that can identify optimal solutions among various parameters in domain both static and dynamic characteristics of control devices remains a critical challenge [9].

This work focuses on the parametric optimization method applying for phase-invariant control devices (VCA, amplifiers, etc.). Currently, the choice of parameters for such devices depends seriously on the intuitive approach of designers, leading to results that differ significantly from those potentially achievable [10].

A new parametric optimization approach based on the Grey Wolf Optimization (GWO) method is investigated [11]. This bioinspired algorithm, which mimics the hunting process of a pack of wolves, demonstrates high extremum detection accuracy and efficient convergence rate, making it a promising tool in the research field.

The rest of this paper is organized as follows. Section II presents the literature review. Section III is devoted to the description of the concept of the optimization method used and its application to the specific problem of the paper. Section IV discusses the achieved and expected results, and Section V concludes the study.

II. STATE OF THE ART

Phase invariant devices are systems designed to maintain independence of phase-frequency response variations during attenuation control. The necessity of achieving phase invariance during gain control to minimize phase variations resulting from gain changes remains critical, as highlighted in [12]. This concept was introduced to ensure the stability and predictability of technical systems in the conditions of variable input data. However, maintaining phase invariance in practice is challenging. It requires optimal synthesis of devices with adjustable gain and phase shift that depend on each other [13]. Specifically, delay control should not significantly alter the shape of the amplitude-frequency response (AFR) within the frequency band, and AFR control should not impact the phase-frequency response (PFR).

The phase-invariance problem is given considerable attention in the monograph [14]. Within this context, the paper examines a simple structure of VCA. This device is used to adjust the gain in receivers to prevent sensitivity degradation and distortion caused by saturation. In transmitters, VCAs are used in vector modulators and to control the output power level. There are no reactive elements such as coil and capacitor in an ideal VCA. As a result, in such system the phase is zero and the device operates over an infinite frequency band. In this case, parametric optimization is reduced only to the problem of finding the optimal values of control elements under the criterion of maximizing attenuation, such as identifying the minimum value of the modulus of the transfer function. In reality, the device contains reactive elements, resulting in a phase shift that differs from zero. In this sense, a multi-criteria optimization is necessary. It is not only important to maximize the attenuation, but also to minimize the phase difference in order to preserve the phase invariance of the device.

As discussed in [15], classical algorithms for solving optimization problems of devices with variable states are not universally applicable. The complexity of these problems is attributable to their multicriterial nature and the numerous parameters involved. Consequently, it is necessary to explore more contemporary approaches.

In recent decades, metaheuristic optimization methods have garnered significant attention, with prominent examples including genetic algorithms [16], ant colony optimization [17], and particle swarm optimization [18]. These algorithms draw inspiration from physical phenomena, animal behavior, and evolutionary concepts. Their simplicity enables the integration of multiple metaheuristics and their application to a wide range of problems. In contrast to gradient-based optimization approaches [11], metaheuristics optimize problems in a stochastic manner, beginning with a random solution and circumventing the need to compute derivatives of the search space. Furthermore, they exhibit a superior capacity to circumvent local optima compared to traditional optimization methods. The extensive range of metaheuristic algorithms, in conjunction with their hybridization and ongoing research, is substantiated by the No Free Lunch (NFL) theorem [19], which posits that no single metaheuristic is universally optimal for all optimization problems. A specific metaheuristic may demonstrate robust performance on one problem set while yielding suboptimal results on another.

The bioinspired optimization algorithm GWO, introduced and analyzed in [20], was developed in 2014. This method simulates the enclosure hunting of a pack of grey wolves. According to the findings reported in [21], the algorithm has demonstrated consistent performance in terms of accuracy in finding the extremum and convergence rate across various functions. Notably, the GWO algorithm exhibits superior convergence speed, attaining an acceptable solution in all test functions after just 100 iterations, irrespective of problem dimensionality. A comparative analysis reveals that the GWO algorithm surpasses the performance metrics of the classical bioinspired particle swarm optimization algorithm.

Many studies have been devoted to the use and modifications of the GWO method [22–25], where strategies to improve the population, parameters, and search mechanism are proposed. It was decided to investigate its concept in the implementation of parametric optimization of phase-invariant control devices because of popularity and high performance of this algorithm.

III. METHODS

In this study, the GWO algorithm is the primary method employed. This metaheuristic stochastic algorithm has demonstrated strong performance on the test functions, both in terms of convergence rate and accuracy in finding extremum. The algorithm is based on the hunting model of a pack of grey wolves, consisting of three leading individuals: the alpha, beta, and delta wolves, representing the top three solutions. All other solutions are classified as omega wolves, the weakest and lowest ranking wolves in the pack. The leading wolves guide the movement of the omega wolves to finally find the globally optimal solution. Every iteration of the algorithm is represented by three stages: the encircling, chase and attack phases.

1. The Encircling Phase

Grey wolves use the following formula for updating positions to surround their prey while hunting (1):

$$X_{i,j}^{t+1} = X_{p,j}^{t} - AD,$$

where $X_{i,j}^{t+1}$ represents the *j*-th coordinate of the *i*-th wolf at time *t*+1, $X_{p,j}^{t}$ constitutes the *j*-th coordinate of the prey at time *t*, *p* indicates the prey, and *D* denotes the distance between the grey wolf and the prey

$$D = \left| C X_{p,j}^{t} - X_{i,j}^{t} \right|,$$

where $X_{i,j}^{t}$ is the *j*-th coordinate of the *i*-th wolf at time *t*, and *A* and *C* are coefficients:

$$A = 2 r_1 a - a, \qquad (1)$$

$$C = 2 r_2,$$

where r_1 and r_2 are random numbers uniformly distributed within the range (0,1), and the coefficient *a* decreases linearly from 2 to 0 and can be articulated as follows:

$$a = 2 - \frac{2t}{I_{\max}},$$

where $I_{\max}$ represents the upper limit of iterations.

2. The Chase Phase

When a pack of wolves is hunting, it is generally considered that the alpha, beta and gamma wolves have the best understanding of the prey location. In this context, the leading wolves positions are considered as the approximate prey location, and these three coordinates are used to estimate the actual prey location.

Simultaneously, other wolves in the pack update their positions based on the coordinates of the leading wolves, gradually approaching the prey. The final position of any wolf under consideration is defined as:

$$X_{i,j}^{t+1} = \frac{X_{\alpha,j}^{t} - A_1 D_{\alpha} + X_{\beta,j}^{t} - A_2 D_{\beta} + X_{\delta,j}^{t} - A_3 D_{\delta}}{3},$$

where $X_{\alpha j}^{t}$, $X_{\beta j}^{t}$, $X_{\delta j}^{t}$ stand for the *j*-th coordinates of alpha, beta and delta wolves, which are the three best solutions at time *t*. A_1, A_2, A_3 represent coefficients, and they can be calculated according to the formula (1). D_{α}, D_{β},

D_δ are the distances between the grey wolf and alpha, beta, and delta wolves, respectively (Fig. 1).

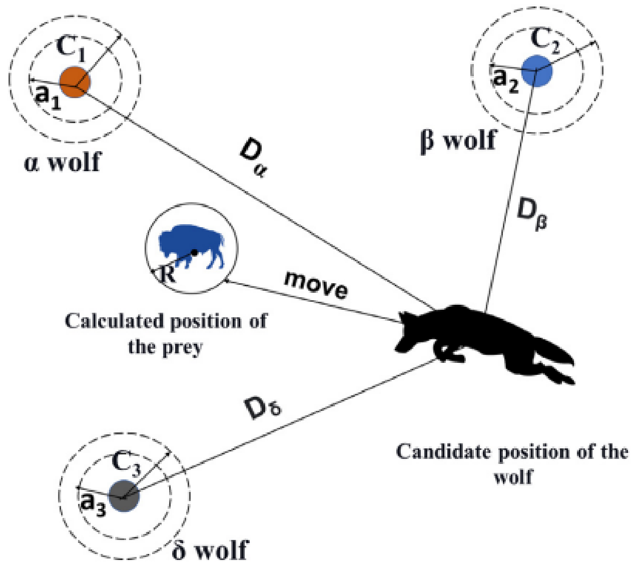

Fig. 1. Position update mechanism of GWO

3. *The Attack Phase*

The predatory behavior of grey wolves is initiated upon the cessation of movement by the prey, a phenomenon governed by the parameter A. The range of values for A, as delineated in equation (1), is constrained within the interval $[-a, a]$, thereby signifying the values from –2 to 2.

When $|A| > 1$, a pack of wolves is relatively dispersed and actively engaged in global exploration to identify general areas where prey may be located. This exploration enables wolves to cover a wider area and gather new information about prey locations.

As the value of a decreases, so does $|A|$. When $|A| < 1$, grey wolves transition to a local search phase, focusing on exploiting available resources and information about the prey location, which signals the initiation of an attack.

Therefore, parameter A is a crucial indicator of whether wolves are in the exploration phase (global search) or the exploitation phase (local search and attack). This adaptability allows grey wolves to optimize their actions according to changing hunting conditions and the location of prey.

This method is used in the present study to identify the optimal parameters of phase-invariant systems. Each wolf symbolizes a set of device parameters that are entered into a target function. In this function, the optimization criteria values are calculated, which are subsequently transmitted to the GWO algorithm.

IV. RESULTS

1. During the analysis of various random parameters of the unoptimized classical attenuator circuit, it was found that the maximum phase difference is observed at the boundary operating frequency. Consequently, the following optimization criteria were formulated for the algorithm to be implemented:

$$\Delta\varphi(K,\omega_b) = \varphi(K,\omega_b) - \varphi(K_{\min},\omega_b) \to \min,$$

$$K(\omega) - K_{\min}(\omega_b) \to \max,$$

where $K_{\min}$ is the minimum (initial) gain or attenuation value of the device; ω_b is boundary angular frequency; $\Delta\varphi(K,\omega_b)$ is phase shift, defined as the phase difference between the initial and the desired value of the transmission coefficient.

2. Determined optimization parameters – correction circuits and elements with controlled resistance of regulating devices.

3. Implemented an algorithm for parametric optimization of the simplest attenuator circuit using the GWO method.

4. Iterative plots of AFR (Fig. 2) and PFR (Fig. 3) are constructed to observe the performance during the process of improving the selection of system parameter sets [26].

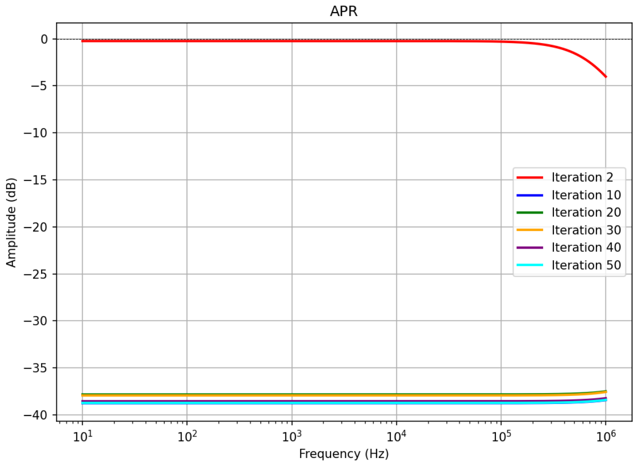

Fig. 2. An example of iterative changes of AFR for a simple attenuator circuit in the process of optimization of parameters

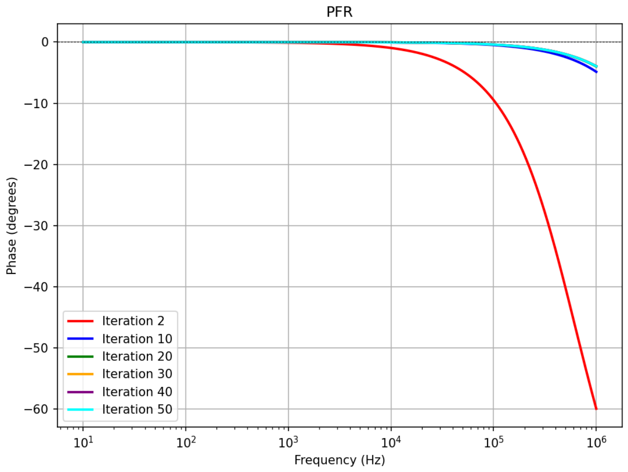

Fig. 3. An example of iterative changes of PFR for the simplest attenuator circuit in the process of optimization of parameters

Presently, the development of the algorithm is still underway, with the objective of achieving universal applicability across diverse device structural configurations.

V. CONCLUSION

This study carried out the multi-criteria optimization of phase-invariant devices using the bioinspired GWO method to identify optimal system parameters crucial for ensuring signal quality in modern electronic systems.

The results demonstrate the effectiveness of the GWO approach, significantly enhancing the parameters of the attenuator by minimizing phase shift. These findings have direct implications for developing novel, efficient devices that meet contemporary requirements for communication systems in electronics.

Future research avenues involve a comprehensive investigation of metaheuristic methods in various fields of electronics and the development of algorithms capable of addressing more complex multi-objective optimization challenges. This work could pave the way for innovative design and optimization strategies for highly sensitive devices, thus facilitating advancements in 5G, satellite navigation, and radar technologies.

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Оптимизация фазоинвариантных устройств с переменными состояниями методом оптимизации стаи серых волков

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Аннотация **– Для современной техники связи важным схемотехническим направлением является разработка электрически управляемых аттенюаторов и регулируемых усилителей, способных изменять амплитуду сигнала в системах с различными установившимися состояниями. Для обеспечения качества передачи сигнала в системах связи крайне важно свести к минимуму влияние паразитных реактивных элементов на фазовый сдвиг при регулировании усиления. Очевидно, что методы**

оптимизации, разработанные для таких устройств, часто приводят к физически неосуществимым решениям. Это явление можно объяснить многоэкстремальностью целевой функции. В данном исследовании проводится многокритериальная оптимизация фазоинвариантных устройств с использованием метода биоинспирированной оптимизации «стаи серых волков» (Grey Wolf Optimization, GWO), который показывает высокую эффективность в поиске оптимальных решений.

***Ключевые слова* – фазовая стабильность, многокритериальная оптимизация, электрически управляемый аттенюатор, оптимизация стаей серых волков, групповое время запаздывания, фазовый сдвиг**

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