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Research Article

Finding the PID Controller Parameters in Synchronization Between Hyperchaotic Oscillators in QAM (Quadrature Amplitude Modulation) Communication System Using Particle Swarm Optimization

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Abstract **–** Oscillators, which form the basis of chaotic communication, can be designed using different mathematical models. Hyperchaotic oscillators, unlike classical chaotic oscillators such as Chua and Sprott, have been developed to generate more chaotic signals. To ensure synchronization of such oscillators, the controller coefficients were determined using particle swarm optimization. This study attempted to achieve synchronization between hyperchaotic oscillator systems using various optimization algorithms, and the results demonstrated that the PID controller was inadequate for these systems.

Keywords – Hyperchaotic Oscillator, Synchronization, Metaheuristic Optimization Algorithms.

I. INTRODUCTION

Quadrature amplitude modulation (QAM) is a technique that combines both amplitude and phase variations in a carrier signal simultaneously. This technique enables higher data rates within the same bandwidth. Refer to the sidebar on spectral efficiency. It involves transmitting multiple bits during each symbol interval of the carrier. The term "symbol" refers to a specific combination of phase and amplitude. The letter "M" in M-QAM indicates the number of bits transmitted per symbol or interval for each unique amplitude and phase combination [1].

Hiperkaotik osilatörler, kanal sayısının ve matematiksel ifadesinin farklı olması sebebiyle geleneksel kaotik osilatörlerden ayrılmaktadır. Bu kaotik osilatörler genelde dört veya daha fazla kaotik sinyal üretmektedirler[2]. Owing to their inherently nonlinear and deterministic dynamics, chaotic signals exhibit aperiodic and broadband behavior during oscillation. These characteristics render them particularly suitable for secure communication applications, where they are employed to obscure transmitted information and mitigate the risk of interception or unauthorized decoding [1, 2, 3]. However, the utilization of chaotic signals for data masking introduces significant challenges related to synchronization at the receiver end. Despite the use of nominally identical chaotic oscillators at both the transmitter and receiver, practical mismatches and parameter sensitivities often lead to desynchronization during real-time operation. To address this, a variety of synchronization methodologies ranging from complete and generalized synchronization to adaptive and observer-based schemes have been extensively investigated [4, 5, 6, 7, 8].

In chaotic communication systems, achieving reliable synchronization typically requires the transmission of auxiliary signals across multiple parallel channels, increasing both bandwidth demand and system complexity at the transceiver ends [9, 10, 11]. To overcome these limitations, various multiplexing techniques encompassing both analog and digital domains have been proposed and implemented, aiming to enhance spectral efficiency and minimize hardware overhead while maintaining robust synchronization and data integrity [12, 13, 14, 15]. Nature has always been a source of inspiration for scientific advancements. Many tools and devices we use in our daily lives have been developed inspired by nature. For example, automobiles, airplanes, and the helicopter, which can be considered the prototype of TRMS, are examples of these innovations. Today, the biological behavior of animal herds has pioneered studies in the field of artificial intelligence. Optimization methods inspired by the collective action of herds provide significant advantages in solving complex computational problems. In this respect, metaheuristic algorithms have contributed to the effective solution of optimization problems encountered in real life. However, the success of these algorithms depends on correctly determining which real-world problem the designed algorithm is suitable for [16]. Particle Swarm Optimization (PSO), which is widely used today and forms the basis of many algorithms, operates according to a specific objective function. This objective function aims to maximize or minimize the target. This method, based on the "swarm intelligence" field of artificial intelligence, has been successfully applied in many areas such as healthcare, environment, industry, commerce, and smart cities [16,17].

II. MATERIALS AND METHOD

A. Hyperchaotic Oscillator System

In the present study, a four-dimensional (4-D) Lorenz chaotic oscillator was employed, capable of generating four distinct chaotic state signals. This oscillator was utilized symmetrically at both the transmitter and receiver ends of the communication system. The mathematical formulation of the 4-D Lorenz chaotic oscillator is provided in Equation (1). [2].

$$\begin{aligned} \frac{dx}{dt} &= a(y-x) - ew \\ \frac{dy}{dt} &= xz - hy \\ \frac{dz}{dt} &= b - xy - cz \\ \frac{dw}{dt} &= ky - dw \end{aligned} \tag{1}$$

In Equation (1) above, the parameters a, b, c, d, k, e, and h are assigned the following values, respectively: $a = 5$, $b = 20$, $c = 1$, $d = 0.1$, $k = 0.1$, $e = 20.6$, and $h = 1$. The initial conditions for the chaotic state variables x, y, z, and w are set to 3.2, 8.5, 3.5, and 2.0, respectively.

B. Quadrature Amplitude Modulation

In this study, an analog Quadrature Amplitude Modulation (QAM) scheme was employed to facilitate the simultaneous transmission of two independent signals over a single communication channel. This was accomplished by modulating each signal onto carrier waveforms that are phase-shifted by 90 degrees with respect to one another. The orthogonality of the carrier phases commonly referred to as quadrature enables the decomposition of the composite signal into its in-phase (I) and quadrature-phase (Q) components, thereby allowing efficient multiplexing within the amplitude modulation framework.

To realize this modulation strategy within a chaotic communication paradigm, a custom-designed chaotic oscillator circuit was integrated into the system architecture. This integration involved modifications and extensions to the baseline circuit configuration depicted in the block diagram of Figure 8.5. The resulting implementation ensures compatibility between the QAM-based modulation scheme and the inherent nonlinear dynamics of the chaotic signals, thereby enabling coherent operation within the context of chaotic signal transmission.

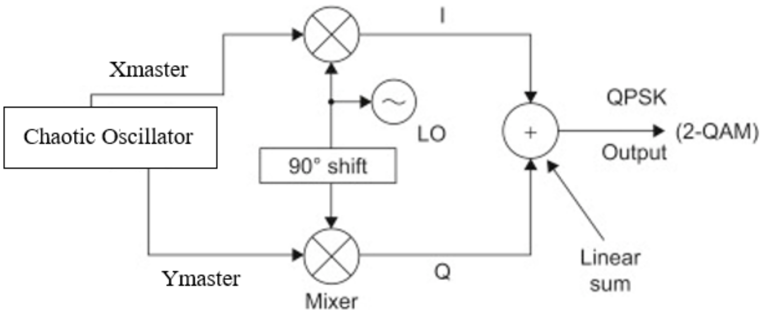

Fig.1 Local oscillator

Quadrature Amplitude Modulation (QAM) is extensively employed in contemporary communication systems owing to its superior spectral efficiency and capability to support high data throughput. As a core modulation technique, QAM underpins a range of broadband communication technologies, including high-speed internet services such as Digital Subscriber Line (DSL) and cable modem systems, as well as digital cable television broadcasting. Additionally, advanced cellular communication standards such as 4G LTE and 5G New Radio (NR) leverage higher-order QAM constellations to significantly improve data rates and optimize spectral resource utilization within increasingly bandwidth-constrained mobile network environments [1]. In figure 2, QAM transmission channel was given.

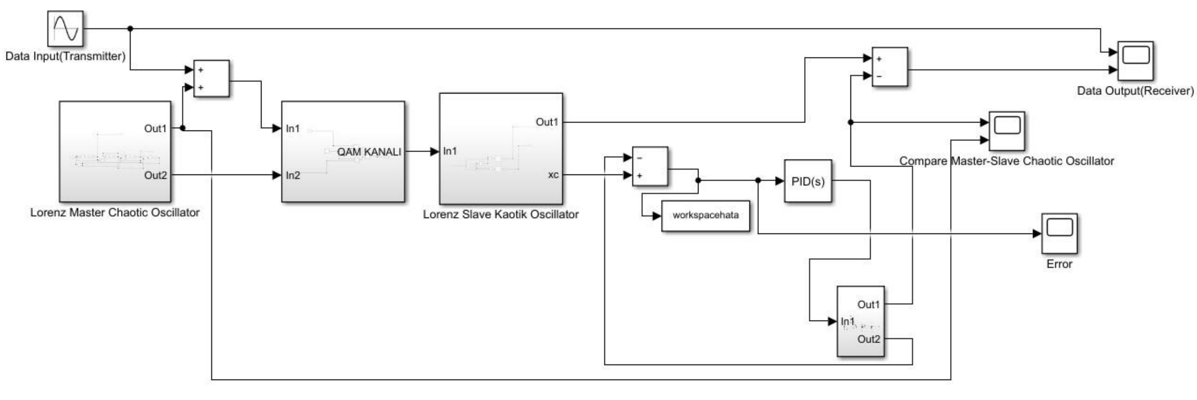

Fig. 2 QAM Transmission Channel

C. Metaheuristic Optimization Algorithms

Particle Swarm Optimization

Particle Swarm Optimization (PSO) operates through a sequence of well-defined stages. The algorithm begins by initializing a swarm of particles with random positions within the defined search space. For each particle, an objective (fitness) function is evaluated to determine its performance. The resulting objective value is then compared to the particle's personal best (pBest). If the current value is better (typically lower in minimization problems) than the pBest, the personal best position is updated accordingly. Otherwise, no changes are made.

Following this, the global best position (gBest) i.e., the best position among all particles is determined by comparing the personal best values across the swarm. Each particle's velocity is then computed based on its current velocity, the distance to its personal best, and the distance to the global best, incorporating both cognitive and social components. Using the updated velocity, the position of each particle is recalculated. Finally, a termination condition is checked—such as a maximum number of iterations or a convergence threshold to determine whether the optimization process should stop.

In MATLAB, the PSO algorithm is typically implemented as a function. Within this function, several key parameters must be defined, including lower and upper bounds for particle positions, cognitive and social acceleration coefficients, swarm size (i.e., number of particles), and the inertia weight. The mathematical formulations for the velocity and position updates in PSO are provided in Equations (2) and (3).

$$v_{k+1} = w * v_k + c_1 r_1 (pbest_k - currentposition) + c_2 r_2 (gbest_k - currentposition) \tag{2}$$

$$x_{(k+1)} = x_k + V_{k+1} \tag{3}$$

In Equation (2), w represents the inertia weight, while r_1 and r_2 are two independent random numbers uniformly distributed in the range (0, 1). The coefficients c_1 and c_2 denote the cognitive and social acceleration factors, respectively.

D. Synchronization

The chaotic oscillators, modeled using MATLAB Simulink, were synchronized in real time. The PID controller parameters utilized for achieving synchronization are presented in Table 1. Based on these PID parameters, the resulting synchronization performance is illustrated in Figure 3.

Table 1. Parameters of PID

Parameters	Kp	Ki	Kd
	29.6395	5.9343	14.1327

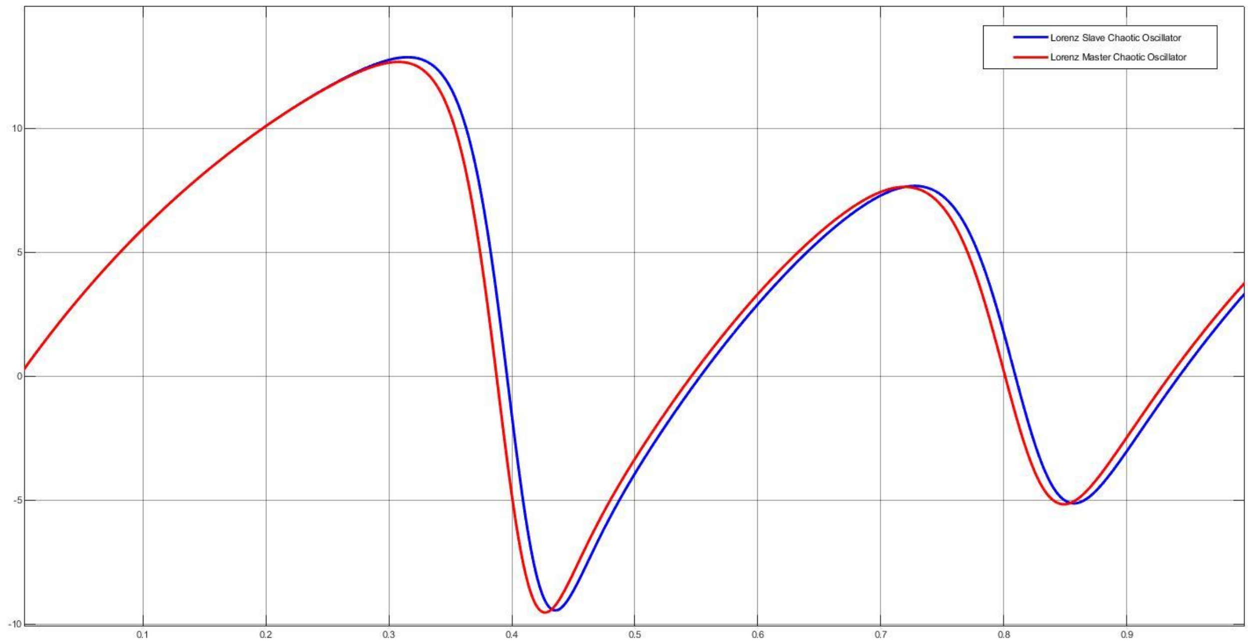

Fig. 3 Synchronization of Hyperchaotic Oscillator (Z_{master} / Z_{slave} Signals)

III. RESULTS

The output signal obtained as a result of the synchronization process was compared with the reference signal, representing the data signals at the transmitter and receiver sides, respectively. The graphical representation obtained from the MATLAB Scope output is presented in Figure 4.

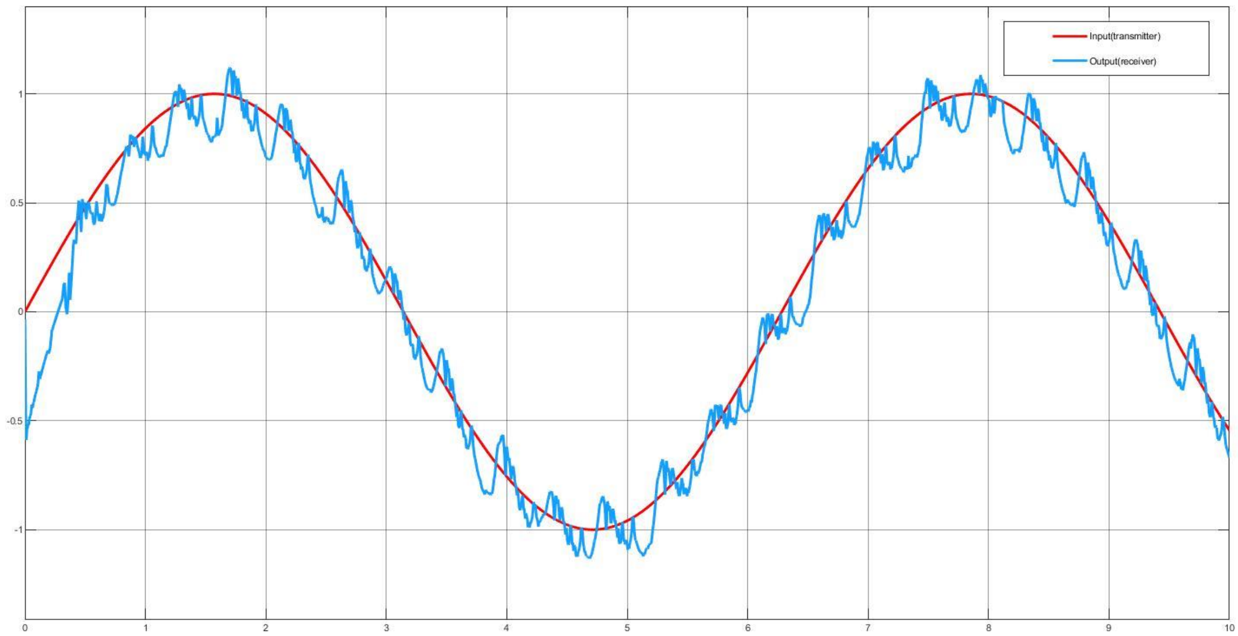

Fig.4 Comparison Input and Output Signals (Data Signals)

As observed in Figure 4, due to incomplete synchronization between the chaotic oscillators at the transmitter and receiver sides, discrepancies were detected in the output signal, indicating the presence of transmission errors.

IV. CONCLUSION

Based on the obtained results, the PID parameters derived through the metaheuristic optimization technique Particle Swarm Optimization (PSO) were not fully effective in compensating for the delays introduced by the modulation and demodulation processes inherent in the QAM-based communication system. As a consequence, the chaotic oscillators at the transmitter and receiver sides failed to achieve complete synchronization, resulting in observable errors in the output signal at the receiver end. Enhancing the synchronization mechanism and mitigating the system-induced delays would lead to improved signal reconstruction quality at the receiver, thereby increasing the overall reliability and performance of the communication system.

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