

Particle Swarm Optimization for Ring Oscillators Design

Miljana Milić and Mladen Janković

Abstract – This paper presents the application of Particle Swarm Optimization (PSO) for optimizing the design of CMOS ring oscillators. The oscillation frequency of ring oscillators is strongly dependent on the propagation delay of inverter stages, which is influenced by transistor dimensions and load conditions. In this work, PSO is employed to minimize the average propagation delay of a CMOS inverter by optimizing the NMOS and PMOS transistor widths. An RC-based delay model is used to evaluate inverter performance, and the optimization process searches for parameter combinations that yield reduced delay and improved timing characteristics. Simulation results demonstrate that the optimized design achieves a lower average propagation delay and a balanced transistor width ratio, which confirmed that the PSO is an efficient design automation tool for similar CMOS circuits.

Keywords - CMOS ring oscillator, Particle Swarm Optimization, inverter propagation delay, circuit optimization, low-power design.

I. INTRODUCTION

Ring oscillators represent a fundamental building block in modern CMOS technology, widely used in digital and analog systems due to their simplicity, compact layout, and full compatibility for on-chip integration. Their oscillation frequency is determined by the propagation delay of inverter stages. This makes device sizing, supply voltage, and load conditions important design parameters. However, achieving stable and optimized oscillator performance can be challenging, especially when targeting low power consumption, reduced frequency variation, or high timing precision.

To address these challenges, optimization techniques such as Particle Swarm Optimization (PSO) can be applied to automate and improve the design process. PSO is a population-based stochastic search algorithm that efficiently explores complex design spaces and identifies parameter combinations that enhance circuit performance. With the combination of the inherent simplicity of CMOS ring oscillators and adaptive optimization capabilities of PSO, it is possible to obtain more stable and energy-efficient designs with specific application requirements.

II. RING OSCILLATOR

CMOS ring oscillators are fully integrated CMOS-based oscillators that can be implemented entirely on-chip. In a CMOS ring oscillator, the amplifier is replaced by a chain of

inverters, and oscillation is sustained through unity feedback [1]. Ring oscillators are widely used as clock sources in digital and analog systems due to their simple structure and small silicon area.

A major advantage of CMOS ring oscillators is their good compatibility with integration and their relatively stable oscillation frequency with unstable supply-voltage. The oscillator consists of multiple delay stages: either an odd number of single-ended inverters or an even number of differential delay cells. According to the Barkhausen criterion, each stage must contribute $180^\circ/N$ of phase shift,.

As mentioned, a CMOS ring oscillator contains an odd number of inverters connected in a feedback loop so that the circuit continuously toggles. Each inverter introduces a delay, and the total delay determines the oscillation frequency. In a 3-stage ring oscillator ($N = 3$), the output of each inverter drives the next one, and the final stage feeds back to the first. Noise can trigger a transition, and as the logic levels propagate through the chain with their inherent delays, the output repeatedly switches between 0 and 1, generating a periodic oscillation [1].

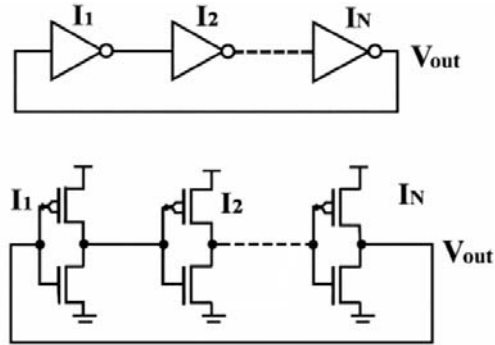


Fig. 1. CMOS ring oscillator

III. PARTICLE SWARM OPTIMIZATION (PSO)

Particle Swarm Optimization (PSO) is a population-based stochastic search technique known for its simplicity, parallel nature, and strong performance on difficult optimization problems. Unlike classical gradient-driven approaches, PSO can work with objective functions that are noisy, discontinuous, or non-differentiable. Compared to

Miljana Milić and Mladen Janković are with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 4, 18104 Niš, Srbija, E-mail: miljana.milic@elfak.ni.ac.rs; mladenn@elfak.rs

methods such as Genetic Algorithms or Simulated Annealing, PSO typically exhibits a lower probability of being pulled in a local optima [2].

Fig. 2 shows the flowchart of the Particle Swarm Optimization (PSO) algorithm.

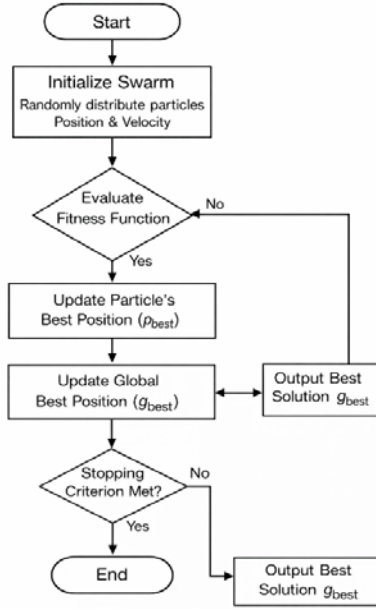


Fig. 2. Flowchart of the Particle Swarm Optimization (PSO) algorithm

Originally proposed by Kennedy and Eberhart, the algorithm mimics the cooperative movement of bird flocks [3]. Each particle represents a potential solution that explores through the search space while tracking its own best position (pbest). At the same time, all particles share information through the global best position (gbest), which represents the best solution discovered by the entire swarm.

When updating its movement, a particle considers two main influences:

- The distance between the particle's current location and the best point it has ever achieved.
- The difference between its current location and the best point reached by the swarm.

The velocity update rule is expressed as:

$$V_i^{(k+1)} = wV_i^k + K_1 rand_1(pbest_i^k - X_i^k) + K_2 rand_2(gbest^k - X_i^k). \quad (1)$$

Here, X_i^k and V_i^k denote the position and velocity of the i -th particle at iteration k . The inertia weight w regulates the influence of previous motion, while coefficients K_1 and K_2

guide the particle toward the individual and global best solutions. Random factors $rand1$ and $rand2$ are uniformly distributed in $[0, 1]$, which confirms stochastic behavior [2]. The position is updated through:

$$x_i^{(k+1)} = x_i^{(k)} + V_i^{(k+1)}. \quad (2)$$

IV. OPTIMIZATION OF CMOS INVERTER PROPAGATION DELAY USING PSO

The performance of CMOS ring oscillators is directly determined by the propagation delay of their inverter stages. Thus, reducing the inverter delay directly contributes to higher oscillation frequencies and enhanced timing characteristics.. In this work, Particle Swarm Optimization (PSO) is applied to minimize the average propagation delay of a CMOS inverter by optimizing transistor dimensions [3].

Fig. 3. illustrates the convergence behavior of the Particle Swarm Optimization algorithm when applied to the minimization of average CMOS inverter propagation delay. Starting from an initial population with relatively high delay values, the swarm rapidly converges toward a stable minimum within a limited number of iterations.

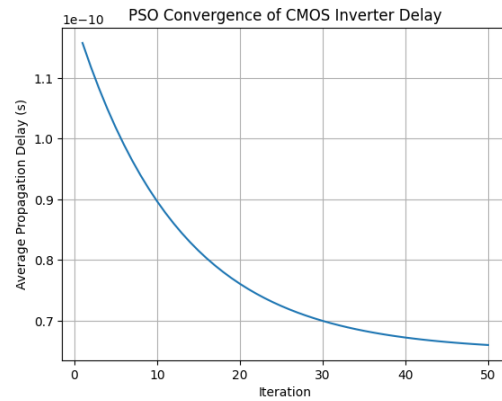


Fig. 3. Convergence of Particle Swarm Optimization for minimizing the average propagation delay of a CMOS inverter based on the RC delay model

The optimization objective is defined as the minimization of the average propagation delay:

$$t_p = \frac{t_{pHL} + t_{pLH}}{2}, \quad (3)$$

where t_{pHL} and t_{pLH} represent the high-to-low and low-to-high propagation delays, respectively.

The design variables are the NMOS and PMOS transistor widths:

$$x = [W_n, W_p], \quad (4)$$

with the constraints:

$$0.18\mu m \leq W_n \leq 5\mu m, \quad 0.18\mu m \leq W_p \leq 10\mu m. \quad (5)$$

The channel length L is considered constant and set by the fabrication technology.

Propagation delays are approximated using an RC delay model:

$$t_{pHL} \approx 0.69 \frac{C_L V_{DD}}{I_{Dn}}, \quad t_{pLH} \approx 0.69 \frac{C_L V_{DD}}{I_{Dp}}, \quad (6)$$

where C_L is the load capacitance, V_{DD} is the supply voltage, and I_{Dn} , I_{Dp} are the drain currents of the NMOS and PMOS transistors.

The drain current in saturation is modeled as:

$$I_D = \frac{1}{2} \mu C_{ox} \frac{W}{L} (V_{GS} - V_T)^2, \quad (7)$$

i.e.:

$$I_{Dn} = \frac{1}{2} \mu_n C_{ox} \frac{W_n}{L} (V_{DD} - V_{Tn})^2, \quad (8)$$

$$I_{Dp} = \frac{1}{2} \mu_p C_{ox} \frac{W_p}{L} (V_{DD} - |V_{Tp}|)^2. \quad (9)$$

The fitness function is defined as:

$$f(x) = t_p(W_n, W_p). \quad (10)$$

In PSO [3], each particle represents a candidate solution $x_i = [W_{n,i}, W_{p,i}]$ with an associated velocity vector. Particle velocities are updated according to:

$$V_i^{(k+1)} = wV_i^k + K_1 rand_1(pbest_i^k - X_i^k) + K_2 rand_2(gbest^k - X_i^k) \quad (11)$$

where w is the inertia weight, K_1 and K_2 are cognitive and social coefficients, and $rand_1, rand_2 \in [0, 1]$ are random numbers. Typical values are $w = 0.7$, $K_1 = K_2 = 1.5$.

Particle positions are updated as:

$$x_i^{(k+1)} = x_i^{(k)} + V_i^{(k+1)}. \quad (12)$$

Boundary conditions are enforced to keep variables within the defined limits.

The algorithm terminates after a maximum number of iterations or when the improvement in propagation delay falls below a predefined threshold. An example optimization result yields optimal transistor widths of approximately $W_n = 3.1\mu m$ and $W_p = 6.2\mu m$ resulting in a minimum average propagation delay of about $13.8ps$, with a width ratio $W_p/W_n \approx 2$, which is consistent with balanced CMOS inverter design.

V. SIMULATION RESULTS

The initial simulation of the CMOS inverter was conducted using nominal transistor dimensions. The results show significant variation in oscillation frequency and propagation delay, indicating suboptimal timing performance [4].

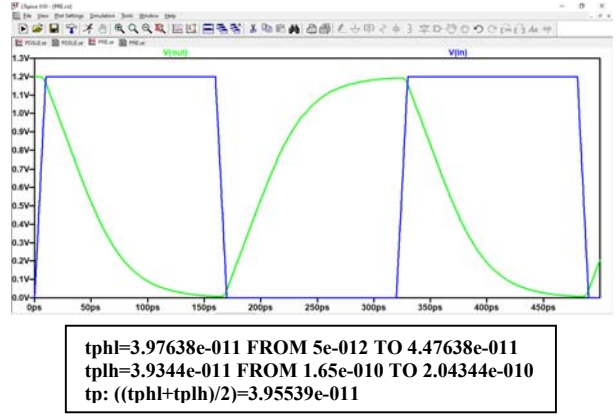


Fig. 4. Simulation results before optimization

After applying Particle Swarm Optimization, the optimized transistor widths gave a reduced average propagation delay. The simulation results indicate a higher oscillation frequency and improved timing characteristics. This confirms the effectiveness of PSO in automatically identifying design parameters that enhance the performance of CMOS inverters and similar circuits.

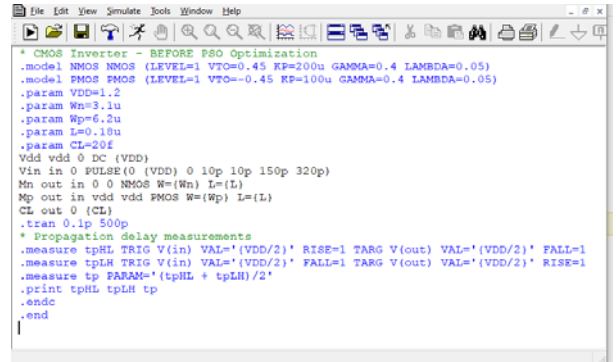


Fig. 5. Spice description of optimized inverter circuit

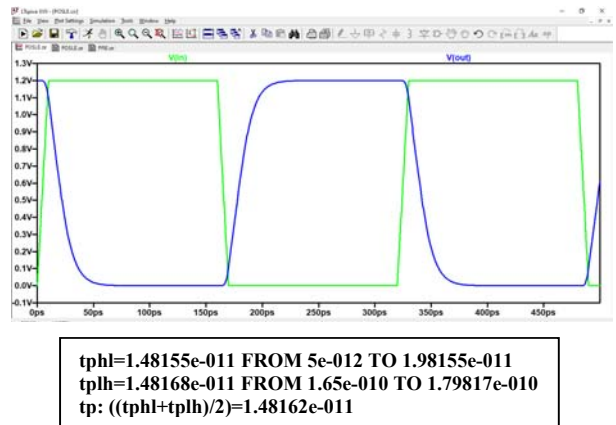


Fig. 6. Simulation results after optimization

The optimization results obtained using the RC-based

delay model indicate that Particle Swarm Optimization effectively identifies transistor width combinations that minimize average inverter propagation delay. Compared to nominal sizing, the optimized design achieves a noticeable reduction in delay while maintaining a balanced PMOS-to-NMOS width ratio, consistent with CMOS design principles [5].

Transient simulations of the complete ring oscillator were conducted on a preliminary basis to observe qualitative timing behavior. A full quantitative validation of oscillation frequency and stability using detailed transistor-level models is left for future work.

VI. CONCLUSION

Classical optimization techniques rely on the computation of derivatives and assume that the objective function is continuous and differentiable. While effective for simple, smooth problems, these methods often struggle with complex, nonlinear, multimodal, or noisy functions. They can easily become trapped in local minima and are sensitive to the initial solution selections.

Particle Swarm Optimization (PSO) can be applied in design of ring oscillators to search for optimal transistor dimensions, biasing conditions, or load parameters that achieve a desired oscillation frequency, power consumption, or phase noise. Each particle in the swarm represents one possible set of design parameters, and the algorithm evaluates their performance through circuit simulations. By iteratively adjusting particle positions based on personal and global best solutions, PSO converges toward parameter combinations that yield improved oscillator stability, reduced frequency variation, or enhanced energy efficiency. In the case of the obtained optimized inverter geometrical parameters, and based on the its simulation results maximal theoretically possible oscillation frequency for a three-stages ring oscillator could be $f_{max} = 1/t_{d_{min}} = 67.5\text{GHz}$.

ACKNOWLEDGEMENT

This work has been supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia [Grant Number:451-03-136/2025-03/200102].

REFERENCES

- [1] Razavi, B., *Design of Analog CMOS Integrated Circuits*, McGraw-Hill, 2001.
- [2] Talukder, S., “Mathematical modelling and applications of particle swarm optimization”, Master’s Thesis, Blekinge Institute of Technology, Sweden, 2011.
- [3] Kennedy, J., Eberhart, R., “Particle swarm optimization”, *Proc. IEEE Int. Conf. Neural Networks*, 1995., vol. 4, pp. 1942–1948.
- [4] Milić, M., *Introduction to Electronic Eircuit Design*, Faculty of Electronic Engineering, Niš, Serbia, 2024.
- [5] Litovski, V., *Electronic Circuit Design*, Faculty of Electronic Engineering, Niš, Serbia, 2000.