Optimization and Neural Network Models for Copper Interconnects

Himanshu Pandey, 2018IMT-038

विश्वजीवनामृतं ज्ञानम्

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Introduction

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- Interconnects are the electronic paths that link various parts of a chip together. These interconnections may be on- or off-chip. Off-chip interconnects are made to join together various chips, whereas on-chip interconnects are made to link components on the same chip.
- There are two classification of interconnects based on the maximum signal propagation distance that it can handle:
  - **Local interconnects**: connects circuit components that are close to one another, such as transistor.
  - **Global interconnects**: can transmit further, for example over subcircuits covering a large area.

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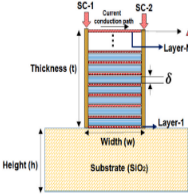

Figure: Structure of Interconnects

Copper as an interconnect

- Copper is an ideal material for interconnects due to its superior electrical and thermal qualities, low cost, and ease of processing.
- Copper's electrical characteristics make it a good connection material. Due to its low resistivity, it offers a high current carrying capacity with minimal power loss.

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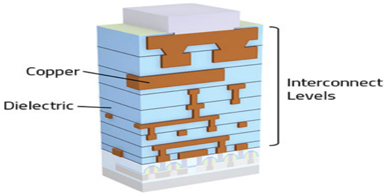

Figure: Copper Interconnects

- Also, copper's resistance doesn't change much with temperature, therefore it has a low thermal coefficient of resistance.
- Copper is also an excellent heat conductor, which is significant in very large scale integrated circuits (VLSI) because heat dissipation is a primary concern in these circuits.

Repeaters in Interconnects

- VLSI circuits have two key design constraints: delay and power dissipation. These develop as a result of the chip's million of active devices and the interconnections between these components.
- In high performance VLSI circuits, it is necessary to reduce propagation latency and power dissipation.
- Repeaters are utilised to reduce connection response time by reducing the effects of resistance and capacitance.

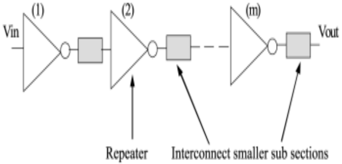

Figure: An interconnect divided into subsections using the repeaters

Key Related Research

Table: Review of key related research

S.No	PaperName and Authors	Description	Limitations
1.	WEN-SHENG ZHAO, PENG-WEI LIU, HUAN YU, YUE HU, GAOFENG WANG, MADHAVAN SWAMINATHAN "Repeater Insertion to Reduce Delay and Power in Copper and Carbon Nanotube-Based Nanointerconnects" Zhao et al., 2019	In this paper, optimal repeater designs for Cu, SWCNT bundle, and MWCNT nanointerconnects are presented. Also discussed is the viability of the ML NN in optimal repeater designs of Cu and CNT-based nanointerconnects.	In practical applications, it is only possible to obtain the circuit parameters experimentally for a specific foundry process at a specific technology node.
2.	Wen Li, Wen-Sheng Zhao, Peng-Wei Liu, Jing Wang, Gaofeng Wang "Optimal repeater insertion for horizontal and vertical graphene nanoribbon interconnects" Li et al., 2020	This paper presents a comparative analysis of repeater insertion designs in horizontal and vertical graphene nanoribbon (GNR) interconnects.	The system is implemented in a limited test area.

Literature Survey

Table: Review of key related research (continued)

S.No	PaperName and Authors	Description	Limitations
3.	Somesh Kumar and Rohit Sharma "Analytical Model for Resistivity and Mean Free Path in On-Chip Interconnects with Rough Surfaces" Kumar and Sharma, 2016	This paper presents a novel analytical model for calculating resistivity and mean free path for on-chip copper interconnects with rough surfaces.	This paper only deals with resistivity and mean free path with not taking into consideration the role of repeaters.
4.	BHAWANA KUMARI, RAHUL KUMAR, ROHIT SHARMA, AND MANODIPAN SAHOO"Design, Modeling and Analysis of Cu-Carbon Hybrid Interconnects" Kumari et al., 2021	(Cu-carbon) hybrid interconnects are a newly proposed interconnection structure where copper-carbon nanotube composite interconnects are encapsulated by graphene barrier layers.	This paper deals with hybrid interconnects models and lack in single element's study.
5.	C. Venkataiah, K. Satyaprasad, T. Jayachandra Prasad"Insertion of an Optimal Number of Repeaters in Pipelined Nano-ICs for Transient Delay Minimization" Venkataiah, Satyaprasad, and Prasad, 2019	This paper demonstrates that a longer interconnect length is the cause of delay during the transient period, and that the optimal number of repeaters is the solution.	This paper deals with optimal number of repeaters only in delay optimized model not involving the power optimized models.

Literature Survey

Table: Review of key related research (continued)

S.No	PaperName and Authors	Description	Limitations
6.	Peng-Wei Liu, Wen-Sheng Zhao, Da-Wei Wang, Jing Wang, Yue Hu, Gaofeng Wang "Optimal repeater insertion for nano-interconnects in current-mode signalling scheme" Liu et al., 2020	In this study, the optimal repeater design for CM nano-interconnects was determined and compared to that of their VM counterparts. In addition, it was demonstrated that the optimal number of repeaters in the CM nano-interconnect is insensitive to the variation in weight of the power dissipation in FoM.	This paper only deals with CM and Vm counterparts of the nanointerconnects not dealing with the mean free path of the interconnect material.
7.	P. Uma Sathyakam, Shubham Raj, A. Karthikeyan and P. S. Mallick" A PSO based optimal repeater insertion technique for carbon nanotube interconnects" Uma Sathyakam et al., 2022	In this paper, the authors propose a particle swarm optimisation (PSO)-based optimal repeater number for carbon nanotube (CNT) interconnects of varying lengths at 20 nm and 14 nm technology nodes.	This paper discusses the optimal number of repeaters in CNT only at two technology nods and lacks in the study of GNR and Cu.

Literature Survey

Table: Review of key related research (continued)

S.No	PaperName and Authors	Description	Limitations
8.	ZI-HAN CHENG, WEN-SHENG ZHAO, DA-WEI WANG, JING WANG, LINXI DONG, GAOFENG WANG, and WEN-YAN YIN"Analysis of Cu-Graphene Interconnects"Cheng et al., 2018	The purpose of this paper is to develop an equivalent single-conductor (ESC) transmission-line (TL) model for analysis of Cu-graphene interconnects, i.e. Cu wires encapsulated with graphene barriers.	This paper only deals with single conductor transmission line and lacks in the study of multi conductor transmission line.
9.	Debaprasad Das"Delay optimization using repeater insertion in folded graphene nanoribbon interconnect systems"Das, 2021	In this paper, the authors explore the optimization of delay using repeater insertion in folded graphene nanoribbon (FGNR) interconnect systems for various nanometer technology nodes. Modeling the mean free path as a function of the GNR width and Fermi energy.	This paper focuses only on the delay optimization of the GNR but do not include the power optimization methods.

Objective

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- Power Delay Product and Delay optimized number of repeaters and optimal repeater size for Copper Interconnects using various optimization algorithms.
- Deploying Artificial Neural Networks for the repeater size and number of repeaters and validating it with best performing optimization algorithm results.

Research workflow

- The main goal of this work is to verify the optimal number of repeaters and repeater size computed theoretically with the PSO, ALO, RS, BA and ANN.
- In our work, we have developed models for various parameters like effective resistivity, mean free path, repeater size and optimal number of repeaters for copper interconnects.
- In case of PSO algorithm we will use a time delay function.
- In case of ANN the relation between the length, specularity parameter, and technology node are taken as inputs and optimal number of repeaters and repeater size are the outputs.

Methodology

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Resistivity for copper Resistivity of copper is calculated using the formula:

$$\rho_s = [\rho_{bulk} + (\rho_{upper/lower} - \rho_{bulk}) + (\rho_{sidewall} - \rho_{bulk}) + (\rho_g - \rho_{bulk})] \tag{1}$$

where

$$\rho_{upper/lower} = \rho_{bulk} \left[1 - \frac{3}{4(t/\lambda_0)} \int_0^1 dq(q - q^3) \times \frac{2(-p_1 p_2 e^{-(t/q\lambda_0)})(1 - e^{-(t/q\lambda_0)}) - (p_1 + p_2)(1 - e^{-(t/q\lambda_0)})^2}{(1 - p_1 p_2 e^{-2(t/q\lambda_0)})} \right]^{-1} \tag{2}$$

Contd.

$$\rho_{sidewall} = \rho_{bulk}\left[1 - \frac{3}{4(w/\lambda_0)}\int_0^1 dq(q-q^3)\times \frac{2(-p_3p_4e^{-(w/q\lambda_0)})(1-e^{-(w/q\lambda_0)}) - (p_3+p_4)(1-e^{-(w/q\lambda_0)})^2}{(1-p_3p_4e^{-2(w/q\lambda_0)})}\right]^{-} \tag{3}$$

$$\rho_g = \frac{\rho_{bulk}}{3}\left[\frac{1}{3} - \frac{\alpha}{2} + \alpha^2 - \alpha^3 \times \ln(1+\frac{1}{\alpha})\right]^{-1} \tag{4}$$

with

$$\alpha = \frac{\lambda_0 R_g}{d(1-R_g)} \tag{5}$$

Methodology

Effective mean free path for copper Effective mean free path for copper interconnect is calcultaed using the formula:

$$\lambda_{Cu} = 3\lambda_0 \times \left[\frac{1}{3} - \frac{\beta}{2} + \beta^2 - \beta^3 \times \ln(1 + \frac{1}{\beta}) \right] \tag{6}$$

with

$$\beta = \frac{\lambda_0 R_f}{D_g(1 - R_f)} \tag{7}$$

where λ_{Cu} is the effective mean free path of copper interconnect, λ_0 is the mean free path of Copper(Cu), R_f is the reflection coefficient.

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Optimal Number of repeaters and repeater size The optimal number of repeaters can be calculated using the formula given in the equation 8:

$$n_{opt} = Inter\left[\sqrt{\frac{R_t C_t}{2R_{d0}(R_{d0} + C_{lo})}} \frac{1}{[1 + 0.21(T_{L/R})^3]^{0.28}}\right] \quad (8)$$

where n_{opt} is the optimal number of repeaters, R_t is the resistance per unit length, C_t is the capacitance per unit length, R_{d0} is the driver resistance, C_{lo} is the driver capacitance and $T_{L/R}$ is the time delay function given in the equation 10.

Contd.

The optimal repeater size can be calculated by using the equation 9:

$$h_{opt} = \sqrt{\frac{R_{d0} C_t}{R_t C_{lo}} \frac{1}{[1 + 0.18(T_{L/R})^3]^{0.26}}} \tag{9}$$

with

$$T_{L/R} = \sqrt{\frac{L_{pul}}{R_{pul}[R_{d0}(C_{d0} + C_{l0})]}} \tag{10}$$

where h_{opt} is the optimal repeater size.

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Particle Swarm Optimization The figure 4 depicts the vectorial representation of the particle swarm optimisation. It also gives us a clear view how the particle velocity and particle position is updated in various interations.

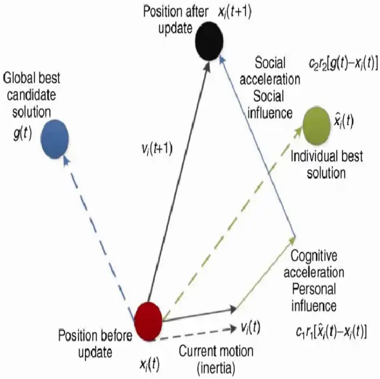

Figure: Vectorial Representation of Particle Swarm Optimisation

Artificial Neural Networks

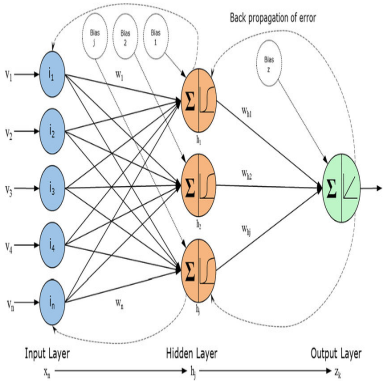

Figure: ANN

Work Done

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- Designed the mathematical functions in python to determine the effective resisitivity, mean free path for copper interconnects for both global and intermediate levels.
- Designed functions for the time delay equation.
- Implemented the PSO, RS, BA, and ALO algorithm to optimize the number of repeaters and repeater size in copper interconnects.

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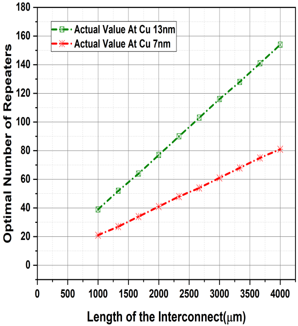

Figure: Optimal Number of Repeaters Computed Analytically

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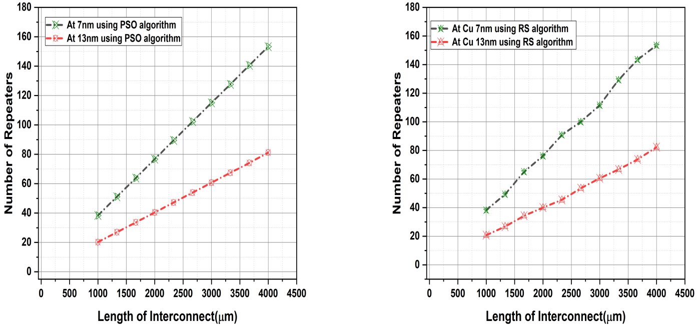

Figure: Optimal Number of Repeaters Computed using Particle Swarm Optimization and Random Search Algorithm

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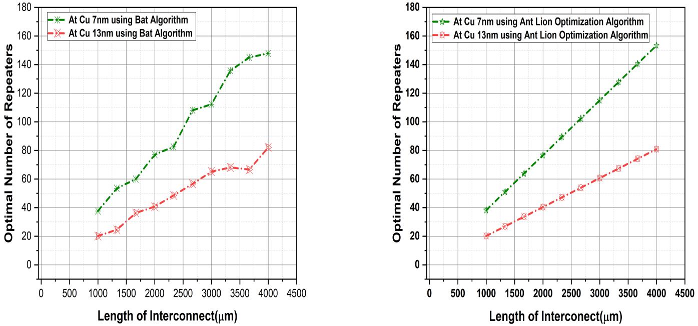

Figure: Optimal Number of Repeaters Computed using Bat Algorithm and Ant Lion Optimization Algorithm

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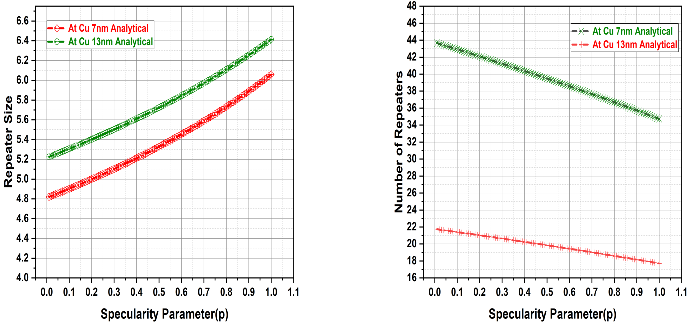

Figure: Repeaters Size and Repeaters Number Computed Analytically

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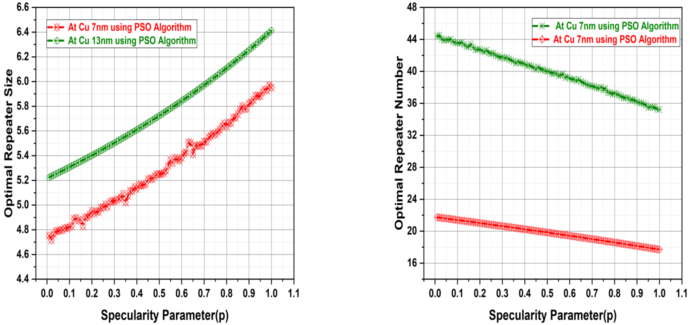

Figure: Repeaters Size and Repeaters Number Computed using Particle Swarm Optimization

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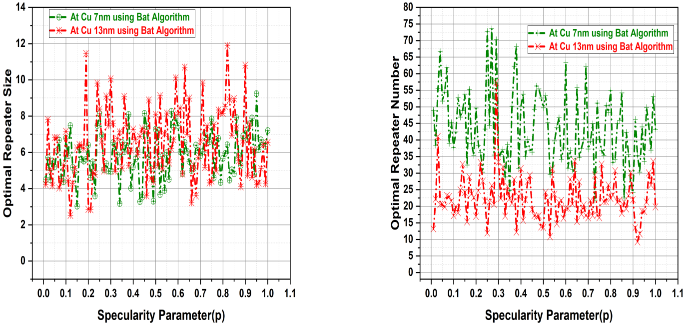

Figure: Repeaters Size and Repeaters Number Computed using Bat Algorithm

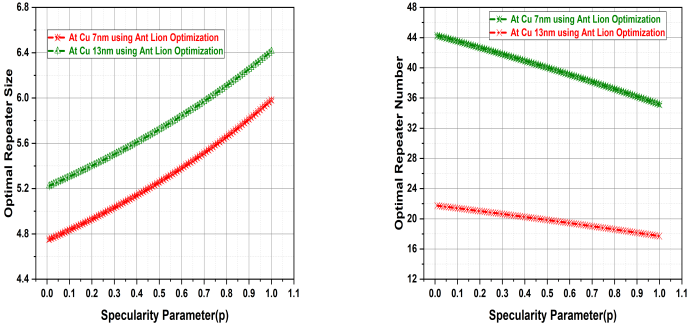

Figure: Repeaters Size and Repeaters Number Computed using Ant Lion Optimization

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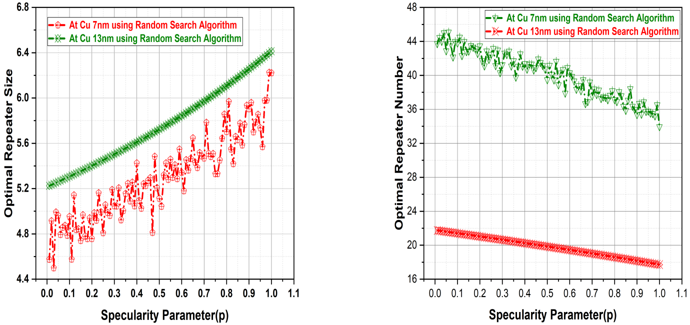

Figure: Repeaters Size and Repeaters Number Computed using Random Search Algorithm

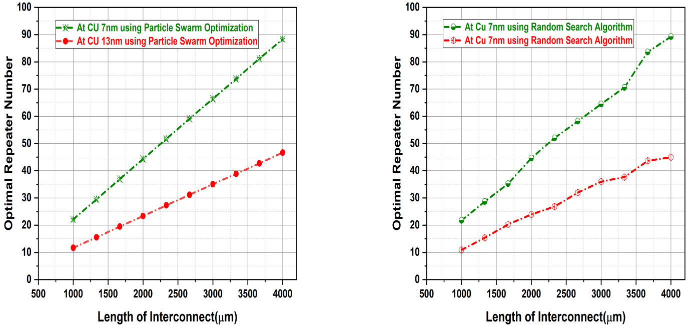

Figure: Optimal Number of Repeaters Computed using Particle Swarm Optimization and Random Search Algorithm

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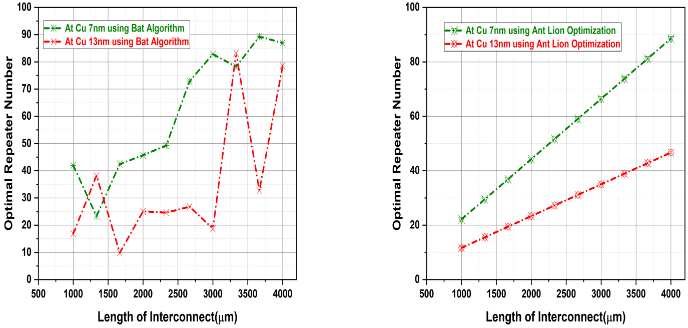

Figure: Optimal Number of Repeaters Computed using Bat Algorithm and Ant Lion Optimization Algorithm

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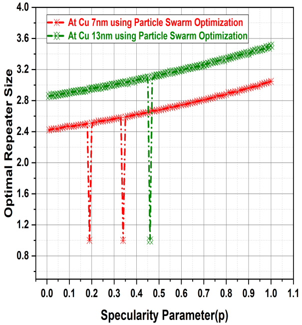

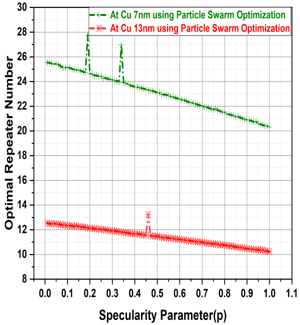

Figure: Repeaters Size and Repeaters Number Computed using Particle Swarm Optimization

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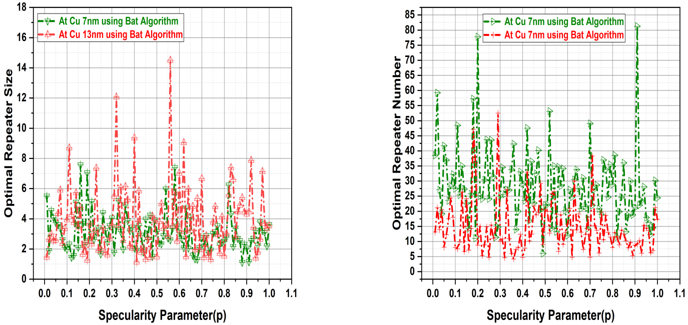

Figure: Repeaters Size and Repeaters Number Computed using Bat Algorithm

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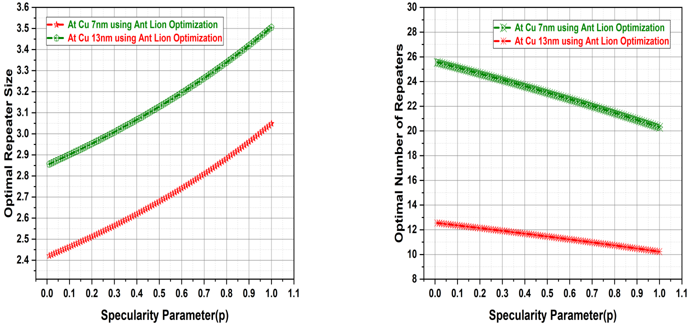

Figure: Repeaters Size and Repeaters Number Computed using Ant Lion Optimization

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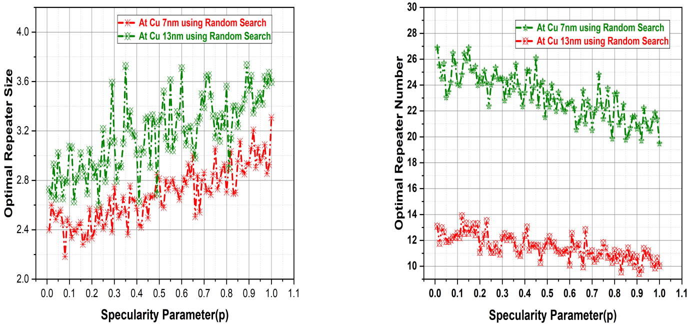

Figure: Repeaters Size and Repeaters Number Computed using Random Search Algorithm

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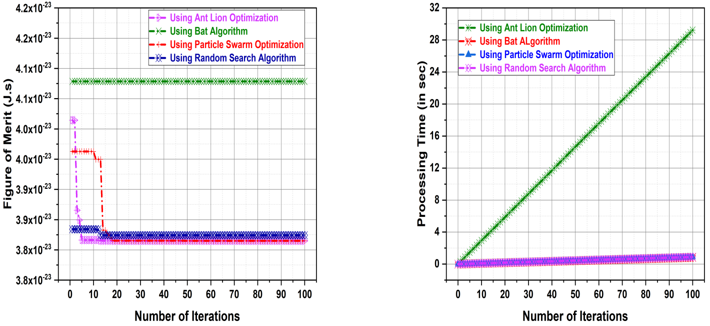

Figure: Figure of Merit and Processing Time for various Algorithms for given Number of Iterations

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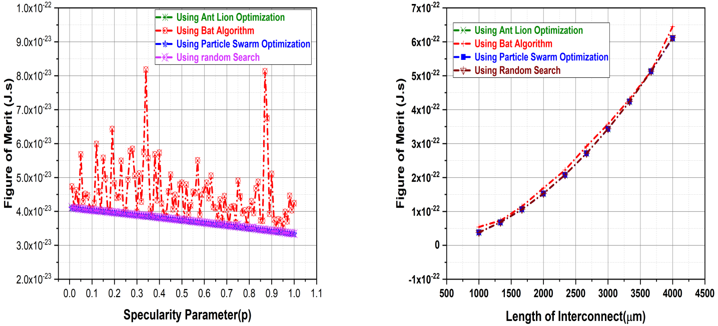
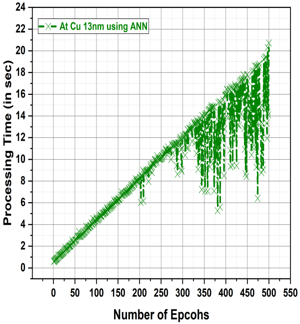


Figure: Figure of Merit Dependency upon Specularity Parameter and length of interconnect for various Algorithms

Artificial Neural Network



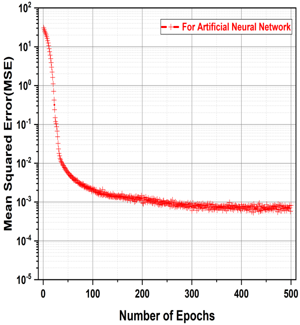


Figure: Variation in the Processing Time and Mean Squared Error on increasing Number of Epochs

Conclusion

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- The effective resistivity of copper interconnect is an important factor in the design and manufacture of various ICs. The next important factor is the effective mean free path of the interconnects. We have designed machine learning models and analytical functions to approximate the value of effective resistivity and mean free path in copper interconnects.
- We have desinged the mathematical models in python to visualise the optimal number of repeaters in copper interconnect at various technology nodes analytically. In this study, we have optimised the number of repeaters and repeater size using all the four PSO, BA, ALO, RS and comparative study is done for all the four algorithms for 7 and 13nm technology nodes in copper interconnects in both time delayed and power delayed product models.

Conclusion

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- From the results obtained, we conclude that among the four optimization algorithms Particle Swarm Optimization is the best one to produce desired results since Bat Algorithm and Random Search fails to produce desired results at some places and Ant Lion Optimization has very high processing time in comparison to Particle Swarm Optimization.
- Further we deployed the Artificial Neural Network producing the similar results to the expectation in few seconds as compared to Particle Swarm Optimization which take 50hours for the same data.

Future Scope

The similar machine learning can be extended to the study of Carbon Nano Tube(CNT) interconnects, Graphene Nanoribbon interconnects(GNR), Cu-CNT, Cu-GNR, Borophene, Cu-BNR and all other interconnects.

These are some references given below: References

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Thank You