

Modeling and Optimization of Advanced Mixed Carbon Nanotube Interconnects

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Abstract: *The rapid technology scaling in VLSI domain leads to a reduction in chip size causing significant impact on performance of system on-chip interconnects. The allotropes of carbon have been proposed as a viable material for futuristic high-speed global VLSI interconnects to overcome the limitations of copper interconnects. Various carbon nanotubes (CNT) configurations have been explored, with the Mixed CNT configuration garnering a lot of attention due to its unique properties and potential as a replacement for copper interconnects in future integrated circuits. For mixed-wall carbon nanotube bundle (MWCNTB) structure, the tube density plays an important role for extracting the parasitic elements associated with MWCNTB interconnects. Here, the tube density of the MWCNTB interconnect has been determined using the new population-based stochastic optimization technique known as colliding bodies optimization (CBO). Initially, this technique is used to generate a random scattering of CNTs in a MWCNTB, to maximize the tube density. Various MWCNTB structures are computationally obtained using this optimization process. For the performance analysis of MWCNTB interconnects, a realistic analytical model for randomly dispersed CNTs in MWCNTB is proposed in the current paper. While in the later stage, performance of MWCNTB structures so optimized is analyzed using SPICE. It is inferred from the study that, the structure with maximum tube density exhibits least latency and power dissipation. Encouragingly, for a fixed cross-sectional area, the overall delay and power dissipation of MWCNTB reduces by 57.3% and 26.06% respectively. The different analyses have been performed at 22 nm technology node.*

Keywords: Carbon Nanotubes, Colliding bodies optimization, MATLAB, Mixed wall CNT bundle, On-chip interconnects, Tube density, SPICE

1. Introduction

Carbon nanotubes (CNTs) have been researched as a potential replacement for copper interconnects as an appropriate solution for integrated circuit interconnects [1-3]. Due to their distinctive characteristics, including high current density, good mechanical tensile strength, and extended ballistic transport length, they are perfect for interconnects in the current nano-scale domain. CNT can be metallic or semiconducting, depending on their chirality's, and metallic CNTs are the preferred candidates for interconnect applications. The structure of single-walled CNT (SWCNT) is formed by wrapping a seamless cylinder of graphene as one atom thick sheet of graphite [4-5]. Each coaxial cylindrical shell that makes up a multi-walled CNT (MWCNT) can have a different chirality depending on how the graphene sheets are rolled up. Due to better development process control, MWCNT production is simpler than SWCNT [6,7]. Researchers have confirmed that all of a MWCNT's shells can conduct if they are properly connected to the contacts, contrary to earlier theories that claimed only the outer shell could conduct. As a result, recent researchers have focused on MWCNT interconnect manufacturing. Depending on how many cylindrical graphene sheets are employed, MWCNTs can range in diameter from a few to hundreds of nanometers. However, it is evident from a fabrication perspective that it is challenging to control the growth of MWCNTs with uniform diameters in a tightly packed bundle [8]. According to reports, a MWCNT bundle with similar diameters is produced with a significant amount of unoccupied space. As a result, the cross-sectional area of the connection is inefficiently used. It is better to build and model the bundles including CNTs of various sizes in order to create a densely packed bundle [9-11].

Wang in [12,13] have reported that tube density is a critical factor to estimate the inductance of MWCNTB interconnects. By achieving higher tube density of MWCNTB interconnects, the crosstalk delay can be reduced [14]. Due to the non-uniform and random distribution of CNTs in MWCNTB, slight extra space is left out during the fabrication process, despite the high conductance and minimal crosstalk latency. It is proposed in literature that tube density plays a prospective role in the performance analysis of MWCNTB interconnects. So, it is necessary to optimize and analyze the MWCNTB interconnect having CNTs of different diameters. Such an optimization between the tube diameters and cross section area of interconnect shall provide a higher tube density. CBO technique is applied here to solve the tube density issue in MWCNTB interconnects.

Kaveh and Mahdavi's newly developed CBO meta-heuristic method is used to address structural difficulties [15-16]. Meta-heuristics are a latest generation of optimization algorithms that have been developed to handle difficult issues [17]. The primary goal of these stochastic search strategies is to replicate natural processes. Darwin's notion of biological evolution inspired the genetic algorithm (GA). Particle swarm optimization (PSO) encourages flocking birds to interact socially. Ant-colony optimization (ACO) mimics ant colonies' ability to determine the shortest path between food and their nest. The musical technique of seeking for a perfect state of harmony was used to develop the harmony search algorithm. In the charged system search (CSS), the charged particles are guided by the Newtonian principles of mechanics and the electric laws of physics. In the current paper, CBO technique is adopted to determine the maximum tube density of MWCNTB interconnects for 22 nm technology node. A one-dimensional collision between two objects served as the inspiration for the multi-agent technique

known as the CBO. Every agent has a body that has a mass and a speed to represent them. When two objects collide, the collision rules change the new positions of the colliding bodies. As a result of the collision, agents move to better places in the search space. The decision variables in the CBO method do not require any internal parameter adjustment (no parameter tuning). Researchers have used the CBO method to address engineering difficulties, and it has been stated that CBO is one of the most successful and superior techniques for optimization challenges [18].

A phenomenon for packing non-uniform diameter circles into a rectangular region has been shown by Huang et al. [19, 20]. Several companies are facing the circle packing challenge, which entails fitting uneven circles into a rectangular, two-dimensional (2D) container (textiles, glass, wood, paper etc.). It includes putting a group of uneven circles in a rectangular container without stacking any of them on top of one another. Increased material utilization and decreased wasteful space are the shared objectives. Therefore, Huang's phenomenon offers a practical method for randomly distributing CNTs with various diameters in a MWCNTB.

The usage of CBO method for on-chip MWCNTB interconnects is discussed in this section. In the later part, the paper is organized as follows: Section II presents Huang's approach which deals with the major constraints of CNTs to be placed randomly in a MWCNTB structure. Section III presents equivalent RLC model of MWCNTB. In Section IV, CBO technique has been applied to determine the tube density of MWCNTB interconnects. Comparative analyses are carried out in Section V. Finally, the conclusion is drawn in Section VI.

2. CNT Distribution in MWCNTB Model

In the following section, a realistic MWCNTB model with a randomly distributed bundle of SWCNTs and MWCNTs with dimensions of width (w) and height (h) is described. The geometry of SWCNT and MWCNT in a bundle is depicted in Fig. 1(a) at a height of ' h ' above the ground plane. Fig. 1(c) shows how CNTs of various diameters can fit in a 2D Euclidean space with the origin as its center. SWCNTs have a diameter known as ' d ', but MWCNTs, which have many shells, having inner-shell and outer-shell diameters known as d_i and d_n , respectively. The inter-shell spacing of the MWCNT in the current fabrication method is equal to the Vander-gap, Waal's or $\delta = 0.34$ nm [31].

The concentric shells of MWCNT structure is presented in Fig. 1(b). The diameter of outer-most shell of MWCNT (d_n) is as given in [21].

$$d_n = d_1 + 2 * \delta * (n-1) \quad (1)$$

where d_n is diameter of outer-most shell, d_1 is diameter of inner-most shell and n represents total number of shells.

The outer diameters for all the CNTs of MWCNTs are assumed as $d_n, d_{n-1}, d_{n-2}, \dots, d_2$ consisting of $n, n-1, n-2, \dots, 2$ shells respectively. The outer diameter of a SWCNT is assumed to be d_1 consisting a single shell. Initially, larger diameters (d_n) of MWCNTs are randomly placed in MWCNTB followed by d_{n-1} and so on up to d_1 . To have a greater number of conducting channels per shell, random

distribution of large diameter to small diameter CNTs is carried out.

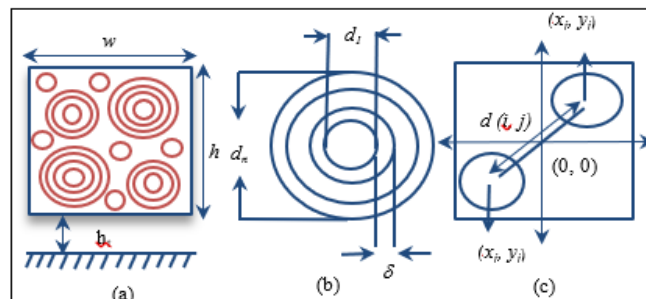


Figure 1: (a) Random distribution of SWCNT and MWCNT in a MWCNTB placed above the ground plane. (b) Geometry of MWCNT. (c) Huang's approach representation

Huang's approach for random arrangement of different sized CNTs in a MWCNTB is utilized. The approach states that if two different diameters of CNTs are d_1 and d_2 placed with center coordinate of (x_i, y_i) and (x_j, y_j) respectively then the following conditions should be satisfied for proper packing of CNTs in MWCNTB model with a center-to-center distance of $d(i, j)$ [12]:

$$\frac{h}{2} - y_i - \frac{d_i}{2} \geq 0 ; \quad i \in \{1, 2, \dots, n\} \quad (2)$$

$$\frac{h}{2} + y_i - \frac{d_i}{2} \geq 0 ; \quad i \in \{1, 2, \dots, n\} \quad (3)$$

$$\frac{w}{2} + x_i - \frac{d_i}{2} \geq 0 ; \quad i \in \{1, 2, \dots, n\} \quad (4)$$

$$\frac{w}{2} - x_i - \frac{d_i}{2} \geq 0 ; \quad i \in \{1, 2, \dots, n\} \quad (5)$$

$$d(i, j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} - \frac{d_i}{2} - \frac{d_j}{2} \geq 0 ; \quad i \neq j \in \{1, 2, \dots, n\} \quad (6)$$

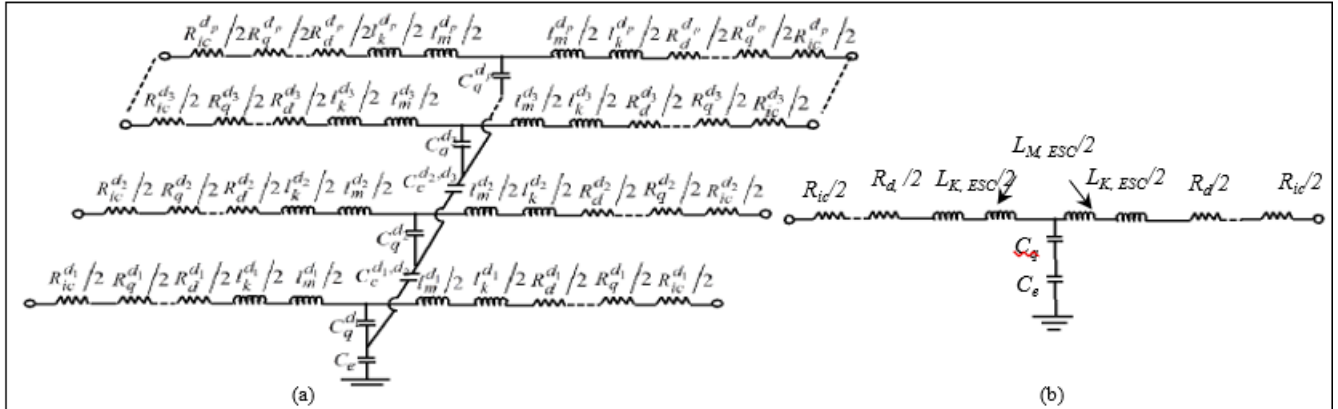
Equations (2)–(5) indicates the position of SWCNTs/MWCNTs within MWCNTB, whereas (6) assures no overlap between any two CNTs in a MWCNTB.

3. RLC Model for MWCNTB System

The behavior of the random distribution of CNTs in a MWCNTB is replicated in this section by a compact multi-conductor transmission line (MTL) model. The total number of conducting channels of each CNT in a bundle, which is mostly determined by the diameter of each SWCNT and MWCNT in a bundle, defines the MTL's interconnect parasitic.

Fig. 2 (a) shows an equivalent electrical model of a MWCNTB based on a random distribution of CNTs of various sizes. Built on the notion that all shells in the MWCNT and all CNTs in the MWCNTB are parallel, the equivalent model is simplified to an equivalent single conductor (ESC) model as per Fig. 2 (b). Based on the fabrication process, value of the contact resistance (R_{ic}) in Fig. 2 (b) may vary up to several hundred k Ω [22–24]. The quantum resistance (R_q) of a CNT is mainly because of low energy levels in a nanowire.

The scattering resistance is due to edge, surface and phonon scatterings [25-27].



$$R_{d,ESC} = \left[\left(\frac{1}{N_{d1}} \left(\frac{R_q}{\sum_{s=1}^n N_{ch,s} \times l_{mfp,s}} \right) \right)^{-1} + \dots + \left(\frac{1}{N_{dn}} \left(\frac{R_q}{\sum_{s=1}^n N_{ch,s} \times l_{mfp,s}} \right) \right)^{-1} \right]^{-1} \quad (7)$$

$$\text{where, } R_q = \frac{h}{2e^2} \quad (8)$$

In (7), $N_{d1}, N_{d2}, \dots, N_{dn}$ denotes the number of CNTs with diameters of $d_1, d_2, \dots, d_n$ in a MWCNTB. The number of conducting channels is denoted by N_{ch} [27]. The mean free path, Planck's constant, and electronic charge are denoted by l_{mfp} , h , and e respectively.

The ESC model of a MWCNTB is shown in Fig. 2(b), and it consists of (i) kinetic inductance ($L_{k,ESC}$), which is caused by kinetic energy having charge that produces current and (ii) magnetic inductance ($L_{m,ESC}$) representing the energy associated with flow of charge carriers through the CNTs [22]. The $L_{k,ESC}$ and $L_{m,ESC}$ in per unit length (p.u.l) are given as [23]:

$$L_{k,ESC} = \left[\left(\frac{1}{N_{d1}} \left(\frac{l_k}{\sum_{s=1}^n N_{ch,s} \times l_{mfp,s}} \right) \right)^{-1} + \dots + \left(\frac{1}{N_{dn}} \left(\frac{l_k}{\sum_{s=1}^n N_{ch,s} \times l_{mfp,s}} \right) \right)^{-1} \right]^{-1} \quad (9)$$

$$\text{where, } l_k = \frac{h}{2v_F e^2} \quad (10)$$

where, $v_F = 8 \times 10^5$ m/s represents the Fermi velocity of the CNT.

$$L_{m,ESC} = \frac{\mu_0}{2\pi} \cosh^{-1} \left(\frac{d_n + 2h_t}{d_n} \right) \quad (11)$$

The equivalent capacitance (C_{ESC}) comprises of (i) electrostatic capacitance ($C_{e,ESC}$) which is due to electric potential difference existing between MWCNTB and ground plane and (ii) quantum capacitance ($C_{q,ESC}$) which represents additional quantum energy needed by the low density of electronic states in CNT. The C_{ESC} , $C_{q,ESC}$ and $C_{e,ESC}$ in p.u.l are expressed by (12) to (14) respectively [25, 30].

$$C_{ESC} = \left(\frac{1}{C_{q,ESC}} + \frac{1}{C_{e,ESC}} \right)^{-1} \quad (12)$$

$$C_{q,ESC} = \frac{2e^2}{h v_F} [N_{d1} \sum_{s=1}^n N_{ch,s} + \dots + N_{dn} \sum_{s=1}^n N_{ch,s}] \quad (13)$$

$$C_{e,ESC} = \frac{2\pi\epsilon}{\cosh^{-1} \left(\frac{h_t}{d_n} \right)} \quad (14)$$

From (7) to (14), it is revealed that the interconnect parasitics depend on the number of CNTs and conducting channels in a MWCNTB. The interconnect parasitics can be reduced if a greater number of bigger diameters CNTs are placed in a MWCNTB. This is because, large diameter MWCNTs contain a greater number of conducting channels. The tube density for a given cross sectional area is stated as:

$$\text{Tube Density, } F = \frac{\sum_{s=1}^n s \times N_{dn}}{w \times h} \quad (15)$$

where, s is varying number of shells from 1 to n .

The current work's main accomplishment is to improve the performance of MWCNTB interconnects by achieving optimal tube density.

4. Optimization Technique

The 1-D colliding bodies optimization (CBO) algorithm is a new multi-agent meta-heuristic algorithm inspired by physical phenomena. Each body or agent or object is specified having some mass and velocity. The agents move to better positions in the search space as a result of these bodies colliding and then separating with new velocity. The intrinsic parameters for the decision variables do not need to be tuned in this method. In terms of numerical results, CBO is competitive and may be simply applied to a variety of engineering optimization tasks.

1) Physical Laws of Collision

Collisions between bodies are governed by the conservation of momentum and energy. As seen in Fig. 3, two bodies having masses of m_1 and m_2 collide in a one-dimensional space. The momentum of all objects before and after collision is equal if there are no external forces acting on them. The conservation of total momentum requires that the total momentum before and after a collision be the same, as shown by the equation:

$$m_1 v_1 + m_2 v_2 = m_1 v'_1 + m_2 v'_2 \quad (16)$$

Similarly, total kinetic energy conservation is represented as:

$$\frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 = \frac{1}{2} m_1 v'^2_1 + \frac{1}{2} m_2 v'^2_2 + Q \quad (17)$$

where v_1 and v_2 are the initial velocities of first and second body before collision, v_1' and v_2' are the final velocities of first and second body after collision, m_1 and m_2 are the masses of first and second body and Q is the loss of kinetic energy due to collision.

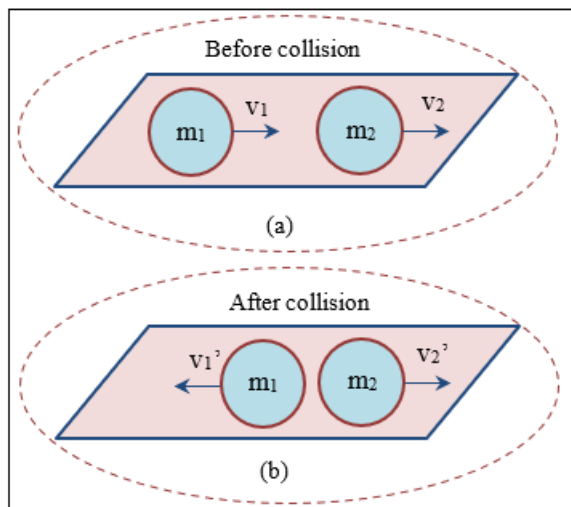


Figure 3: Pair of bodies (a) before and (b) after collision.

The following are the formulas for velocities after a one-dimensional collision:

$$v_1' = \frac{(m_1 - \varepsilon m_2)v_1 + (m_2 + \varepsilon m_2)v_2}{(m_1 + m_2)} \quad (18)$$

$$v_2' = \frac{(m_2 - \varepsilon m_1)v_2 + (m_1 + \varepsilon m_1)v_1}{(m_1 + m_2)} \quad (19)$$

where ε is the two colliding bodies' coefficient of restitution (COR), defined as the ratio of relative velocity of separation to relative velocity of approach.

$$\varepsilon = \frac{|v_2' - v_1'|}{|v_2 - v_1|} = \frac{v'}{v} \quad (20)$$

Any collision has two particular instances, according to the coefficient of restitution: (i) A fully elastic collision is defined as one in which no kinetic energy is lost during the collision ($Q = 0$, $\varepsilon = 1$). The separation velocities are high in this area. (ii) ($Q \neq 0$ and $\varepsilon \leq 1$), an inelastic collision occurs when portion of the kinetic energy is converted to another kind of energy during the impact. COR does not equal one in this example. Separation velocities are minimal in this area. The value of ε is between 0 and 1 for the majority of genuine objects.

2) Approach for proposed algorithm

The major goal of this study is to develop CBO, a novel simple and efficient meta-heuristic method. Each solution candidate X_i with many variables (i.e. $X_i = \{x_{ij}, y_{ij}\}$) is regarded a colliding body (CB) in CBO. The CBs are divided into two groups: stationary and moving objects, with the movement objects moving to follow stationary objects and colliding with each other. This is carried out for two reasons: (i) to push stationary objects into better locations; (ii) to enhance the positions of moving objects.

Using the collision laws established in Section IV, new locations of colliding bodies are updated based on new velocity after the contact. In a nutshell, the CBO procedure is as follows:

Level 1: Initialization

Step 1: Assigning w , h and d_n parameters. The control variables include central coordinate values of CNTs.

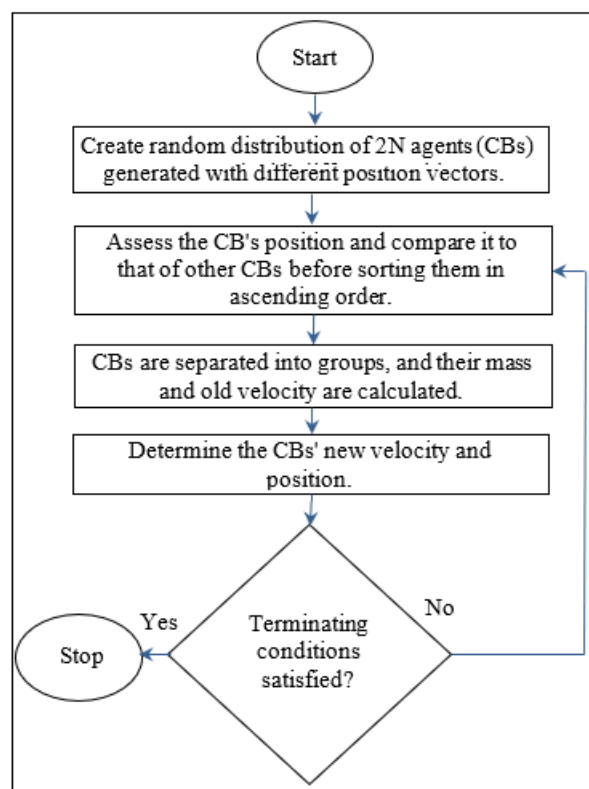


Figure 4: Flowchart of CBO algorithm

These coordinates constitute the pair of individual positions which represent several agents that are randomly generated within their limits and the agents are collectively called as colliding bodies (CBs). The complete search space for CBO algorithm is expressed as follows:

$k = 1, 2, \dots, N_p$ and $m = 1, 2, \dots, N_a$. The numbers N_p and N_a refer to the number of populations and agents, respectively.

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_k \\ \vdots \\ X_N \end{bmatrix} = \begin{bmatrix} (x_{1,1}, y_{1,1}), (x_{1,2}, y_{1,2}), \dots, (x_{1,N_a}, y_{1,N_a}) \\ (x_{2,1}, y_{2,1}), (x_{2,2}, y_{2,2}), \dots, (x_{2,N_a}, y_{2,N_a}) \\ \vdots \\ (x_{k,1}, y_{k,1}), (x_{k,2}, y_{k,2}), \dots, (x_{k,N_a}, y_{k,N_a}) \\ \vdots \\ (x_{N_p,1}, y_{N_p,1}), \dots, (x_{N_p,m}, y_{N_p,m}), \dots, (x_{N_p,N_a}, y_{N_p,N_a}) \end{bmatrix}$$

Level 2: Search (CBs ranking)

Step 2: Sort the diameters from largest to smallest diameter in descending order and select the largest diameter first, followed by the decreasing ones.

Step 3: Calculate the distances for the largest diameter of each agent in CB using (2) to (6) and if it satisfies all the constraints then retain this agent, else select the succeeding agent in the CB.

Step 4: After successful placement of all largest diameter CNTs in MWCNTB, repeat *Step 3* for placing next lower

diameter CNTs until it reaches the least diameter value. Repeat *Step 3* and *Step 4* for all the CBs.

Step 5: Calculate each CB's fitness value using (15).

Step 6: The body mass of each CB is evaluated as,

$$m_k = \frac{1/F(k)}{\sum_{j=1}^{Np} F(j)} \quad (21)$$

where $F(k)$ and $F(j)$ are the fitness values of the k^{th} and j^{th} CB respectively.

Level 2: Search (Group creation)

Step 7: Sort all the CBs in ascending order with respect to their mass values. As shown in Fig. 5, these sorted values are separated into two parts: (i) stationary bodies and (ii) moving bodies.

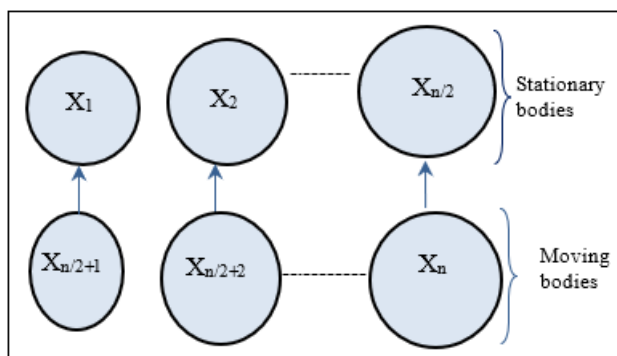


Figure 5: The pairs of CBs for collision

Level 2: Search (Evaluations before the collision)

The stationary and moving body velocities before the collision are expressed as follows:

$$v_k = 0 ; \quad k = 1, 2, \dots, \frac{Np}{2} \quad (22)$$

$$v_k = X_{k-\frac{Np}{2}} - X_k ; \quad k = \frac{Np}{2} + 1, \dots, Np \quad (23)$$

where, X_k is the position vector of the k^{th} CB.

Level 2: Search (Evaluations after the collision)

Step 8: Moving bodies move towards the stationary bodies leading to collisions. The positions of both moving and stationary bodies improve as a result of this. After collisions, the velocities of the stationary and moving bodies are computed as:

$$v'_k = \frac{(m_{k+\frac{Np}{2}} + \varepsilon m_{k+\frac{Np}{2}}) v_{k+\frac{Np}{2}}}{m_k + m_{k+\frac{Np}{2}}} ; \quad k = 1, 2, \dots, \frac{Np}{2} \quad (24)$$

$$v'_k = \frac{(m_k - \varepsilon m_{k-\frac{Np}{2}}) v_k}{m_k + m_{k-\frac{Np}{2}}} ; \quad k = \frac{Np}{2} + 1, \dots, Np \quad (25)$$

where, ε is calculated as below

$$\varepsilon = 1 - \frac{I}{I_{max}} \quad (26)$$

where, I and I_{max} are the current iteration number and the maximum number of iterations respectively.

Level 2: Search (CBs updating)

Step 9: The position of each CB is updated using new velocities (27) and (28).

$$X_k^{I+1} = X_k^I + rand(1, Na) * v_k^I ; \quad k = 1, 2, \dots, \frac{Np}{2} \quad (27)$$

$$X_k^{I+1} = X_{k-\frac{Np}{2}}^I + rand(1, Na) * v_k^I ; \quad k = \frac{Np}{2} + 1, \dots, Np \quad (28)$$

where, X_k^I and X_k^{I+1} are the position vectors of the k^{th} CB in I^{th} and $(I+1)^{th}$ iterations respectively.

Level 3: Terminating condition

Step 10: If any of the agents in a CB hits its limit, set it to the corresponding boundary value.

Step 11: When the maximum number of iterations has been achieved, halt the program and print the maximum tube density as well as the appropriate number of CNTs for each diameter. Otherwise, go to *Step 3*.

5. Result and Discussion

As per the ITRS report for 22 nm technology node, the interconnect dimensions i.e. width and height are 32 nm and 75 nm respectively [28]. A driver-interconnect-load (DIL) system is used to investigate propagation delay and power dissipation for various bundle designs. The ESC model of Fig. 2(b) represents the interconnecting lines in Fig. 6. A CMOS inverter gate is considered as a driver and load for accurate estimation of delay and power dissipation.

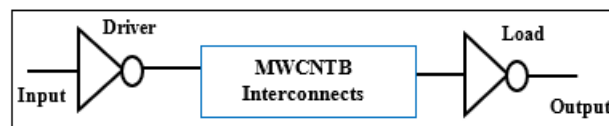


Figure 6: Driver-Interconnect-Load model

Table I: Number of CNTs in MWCNTB structure

CNT bundle structure		Number of CNTs in the interconnect of cross-sectional area (32nm x 75nm) having diameter, N_{Dn} (nm)	
Shell number	Shell diameter (nm)	MWCNTB-I	MWCNTB-II
1	1	31	0
2	1.68	22	0
3	2.36	17	0
4	3.04	9	0
5	3.72	3	0
6	4.4	2	0
7	5.08	2	0
8	5.76	4	0
9	6.44	2	0
10	7.12	11	27
Tube density ($\times 10^{16}/m^2$)		15.125	11.25

In the experimental setup, MWCNTBs are considered having ten different types of CNT shells varying from 1 to 10. The inner-most (minimum) diameter of a CNT shell is assumed to be 1 nm. Using (1), the diameter of the outer-most 10th shell of a CNT is computed to be 7.12 nm. The input signal has a

rise and fall time of 1 ns. The number of CBs and maximum number of iterations are 1000 and 100 respectively. The simulative analyses for delay and power dissipation of different MWCNTB interconnect structures have been performed using Tanner tool (SPICE).

The tube density values obtained for MWCNTB-I and MWCNTB-II are $15.125 \times 10^{16} / \text{m}^2$ and $11.25 \times 10^{16} / \text{m}^2$ respectively is shown in Table I. RLC parameters are evaluated using equations are given in Table II.

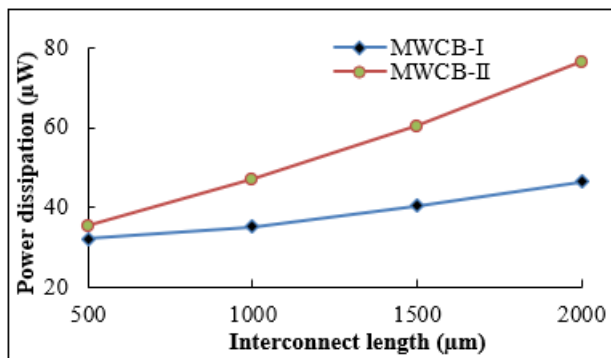


Figure 7: Propagation delay with various interconnect lengths.

Fig. 7 and 8 present propagation delay and power dissipation respectively of different MWCNTB structures for global interconnects. The interconnect length is varied from 500 to 2000 μm . The MWCNTB-I structure with maximum tube density provides significantly lower propagation delay and power dissipation for all interconnect lengths. With increase in tube density, improvement in performance is observed due to the fact that conducting channels are proportional to the number of tubes.

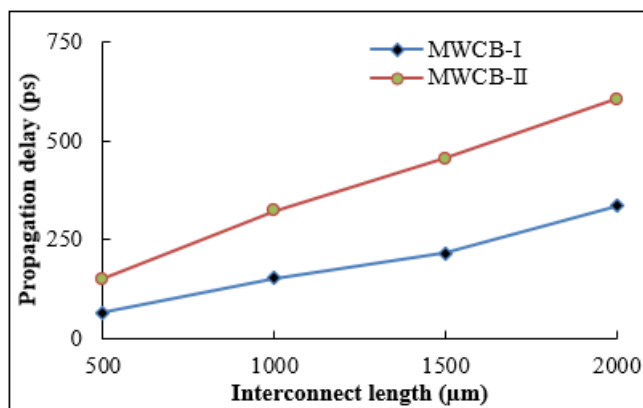


Figure 8: Power dissipation with various interconnect lengths

Table II: RLC parameters for MWCNTB structure

Interconnect Parasitics	MWCNTB-I	MWCNTB-II
Contact Resistance, R_{ic}	35 Ω	48.7 Ω
Scattering Resistance, R_{dESC}	5.58 $\Omega/\mu\text{m}$	7.35 $\Omega/\mu\text{m}$
Inductance, L_{ESC}	14.28 pH/ μm	23.148 pH/ μm
Capacitance, C_{ESC}	25.12 aF/ μm	70.98 aF/ μm

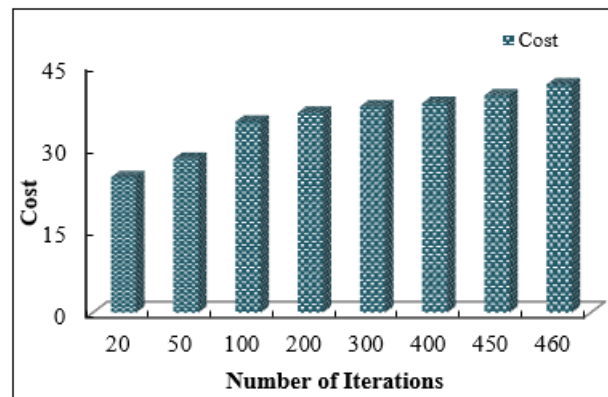


Figure 9: Cost versus number of iterations graph

The percentage of successful convergence is used to assess how reliable the CBO approach is actually. The convergence rate is the proportion of runs out of all trials that successfully converge (i.e., produce the maximum tube density value) [29]. 455 trials from 500 successfully converged here. Thus, the convergence rate obtained is 91 %. The successful convergence rate of 91% confirms the robustness of CBO technique.

6. Conclusion

Differing bundle designs were described in this research paper, where MWCNTs with identical and different numbers of shells were specifically assembled. The analysis of interconnection dependability, including delay and power dissipation depending on bundle arrangements, is done using the ESC model. For random distribution of CNTs of varied sizes in MWCNTB with increased tube density, a colliding bodies optimization technique is proposed in this study. Overall latency and power dissipation have both been reduced by 57.3 percent and 26.06 percent, respectively. For a range of interconnect lengths, the MWCNTB interconnect with higher tube density has a less total delay and power dissipation than the other tube density structure. As a result, MWCNTB with maximum tube density is offered as a better approach for achieving high performance and efficiency in nanoscale integrated circuits. As a result, for future global VLSI interconnects, a mixed CNT bundle may be favored.

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