Dynamic crosstalk analysis of mixed multi-walled carbon nanotube bundle interconnects

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Abstract: Multi-walled carbon nanotube (MWCNT) bundles have potentially provided attractive solutions in current nanoscale VLSI interconnects. From fabrication point of view, it is difficult to control the growth of a densely packed bundle having MWCNTs with similar diameters. A realistic bundle is combination of MWCNTs with different number of shells. Thus, this research work focuses on the analytical model of a bundle having the MWCNTs with different number of shells or in turn different diameters [mixed MWCNT bundle (MMB)]. Based on the multi-conductor transmission line theory, an equivalent single conductor (ESC) model is employed for the proposed MMB arrangements. The ESC model of MMB is used to compare the dynamic crosstalk delay with conventionally arranged bundle containing MWCNTs with similar diameters [MWCNT bundle (MB)] under different input transition time and spacing conditions. It is observed that a realistic MMB correctly estimates the crosstalk delay for the different transition time that overestimates the delay of a conventionally arranged MB by 1.35 times. Moreover, the MMB arrangement reduces the overall crosstalk delay by 47.26% compared with the conventional MB arrangements for an inter-bundle spacing ranging from 5 to 30 nm.

1 Introduction

During the recent past, researchers have considered carbon nanotubes (CNTs) as a potential interconnect material in high-speed electronics because of their unique physical [1], mechanical [2], electrical [3], chemical and thermal properties [4]. The unique atomic structure, formed by rolling of graphene sheet, provides a long mean free path (mfp) in the order of several micrometres [4]. The $sp^2$ bonding of carbon atoms in a graphene sheet makes CNTs a strong material that exhibits a variety of low-power interconnect applications in the areas of microweoelectronics/nanoelectronics [5]. The unique physical properties are mainly because of the structure of CNTs that primarily depends on the chirality, that is, rolling up direction of graphene sheets. Depending on the number of concentrically rolled up graphene sheets, CNTs can be categorised as single- (SWCNTs) and multi-walled CNTs (MWCNTs) [6]. Although the current carrying capability of a metallic SWCNT is similar to that of an MWCNT [1], but an MWCNT exhibits easier control on growth process compared with SWCNTs [7]. MWCNT consists of several coaxial cylindrical shells with different chirality that primarily depends on the rolled up direction of graphene sheets. Thus, MWCNTs have a large diameter ranging from a few to hundreds of nanometres [8]. Depending on the shell diameter, MWCNTs have a higher number of conducting channels and larger mfp in comparison to the SWCNTs. To explore these advantages, majority of the recent research [7–10] has targeted towards the fabrication and modelling of MWCNT interconnects.

From the fabrication point of view, it is quite difficult to control the growth of MWCNTs with similar diameters in a densely packed bundle. Yilmazoglu et al. [10] reported about the fabrication of a bundle with MWCNTs having similar diameter wherein a lot of free space was left out, thereby inefficiently using the space. It has become increasingly difficult to fabricate a densely packed bundle accommodating MWCNTs of similar diameters. Thus, in the current research scenario, it is preferred to fabricate and model the bundles where the MWCNTs of different diameters can be taken care of to achieve a densely packed bundle. To meet such requirements, this research paper presents two different types of CNT bundles: (i) bundles having MWCNTs with equal diameters [MWCNT bundle (MB)] and (2) bundles having MWCNTs with different diameters [mixed MWCNT bundle (MMB)].

Although, several electrical equivalent models for MWCNT have been proposed previously also, but they are inflicted by certain inaccuracies; Li et al. [11] proposed an equivalent resistor inductor capacitor (RLC) model of MWCNT by incorrectly assuming an mfp ($\lambda_{\text{MB}} = 1 \mu m$) independent of the MWCNT shell diameter. In a similar way, Sarto and Tamburrano [8] and Majumder et al. [12] incorrectly considered the mfp and number of conducting channels independent of the shell diameter. This research paper presents an equivalent single conductor (ESC) model of MWCNT bundle by correctly modelling the diameter dependent mfp and number of conducting channels. Using a capacitively coupled interconnect line, the ESC model is used to analyse the crosstalk delay for different transition time and spacing conditions. Interestingly, it is observed that at global interconnect lengths; the crosstalk delay performance is significantly improved for realistic mixed MWCNT bundle (MMB) configuration compared with the conventionally modelled MB arrangements.

The organisation of this paper is as follows: Section 1 introduces the potential application and characteristics of a realistic MWCNT bundle in the context of current research scenario. Section 2 presents an ESC model for the bundles having MWCNTs with equal and different diameters. Section 3 provides a detailed description of capacitively coupled interconnect lines that is used to analyse the dynamic crosstalk delay for different bundle arrangements as demonstrated in Section 4. Finally, Section 5 draws a brief summary of the paper.

2 Geometry and ESC model

This section presents different specified arrangements of MWCNTs in a bundle that primarily depends on the basic geometry of an MWCNT. Initially, a multi-conductor transmission line (MTL) model of MWCNT bundle is employed to obtain different interconnect parasitics such as resistance, capacitance and inductance.
Finally, the MTL model is simplified to an ESC for different MB and MMB configurations.

### 2.1 Arrangements of bundled MWCNT having similar and different number of shells

The geometry of MWCNT above the ground plane is shown in Fig. 1 that consists of several concentric rolled up graphene sheets with diameters $D_1, D_2, \ldots, D_n$. In current fabrication technology, the intershell spacing is approximately equivalent to the Van der Waal’s gap ($\delta$) between neighbouring carbon atoms \[ \delta = \frac{D_n - D_{n-1}}{2} \approx 0.34 \text{ nm} \] where innershell and outershell diameters are represented as $D_1$ and $D_n$, respectively, and $n$ denotes the total number of shells. The distance between the centre of MWCNT and the ground plane is equivalent to $H = \frac{D_n}{2} + h$, where $h$ represents the distance of outermost shell from the ground plane. The outershell diameter of MWCNT primarily depends on the number of shells ($n$) and can be expressed as

\[ D_n = D_1 + 2 \times \delta \times (n - 1) \] (2)

Depending on the geometry of Fig. 1, this sub-section presents three different conventional bundle arrangements (Fig. 2) that consists of MWCNTs of uniform diameters (equal number of shells). Figs. 2a–c exhibit the bundle arrangements of MB-I, MB-II and MB-III, wherein MWCNTs with 4-, 8- and 12-shells are placed, respectively. The total numbers of MWCNTs [11] in terms of bundle height ($h$) and width ($w$) can be expressed as

\[ N_{\text{MWCNT}} = \left[ \frac{N_x N_y - \text{integer} \left[ \frac{N_y}{2} \right]}{2} \right] \] (3)

where

\[ N_x = \frac{w - D_n}{D_n + \delta} + 1 \quad \text{and} \quad N_y = \frac{h - D_n}{(D_n + \delta) \sqrt{3/2}} + 1 \] (4)

where $N_x$ and $N_y$ represent the numbers of MWCNTs in horizontal and vertical directions, respectively.

Fig. 3 presents the arrangements of realistic mixed bundles wherein MWCNTs of different numbers of shells are placed. The mixed bundle follows the arrangements of MWCNTs with a higher number of shells at the periphery, whereas the MWCNTs of smaller diameters are placed at centre of the bundle. The primary advantage behind this type of arrangement indicates minimum unutilised areas that serve densely packed MWCNT bundles. Fig. 3a introduces the arrangement of MMB-I, wherein

Fig. 1 Geometry of MWCNT above ground plane

Fig. 2 Arrangements of MWCNTs with 4-, 8- and 12-shells in

a MB-I
b MB-II
c MB-III

Fig. 3 Arrangements of mixed MWCNT bundles of

a MMB-I
b MMB-II
c MMB-III

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The MWCNTs placed at periphery (MWCNTs having 12-shells and 8-shells, respectively) are placed from periphery to centre. Therefore, the total number of MWCNTs in an MMB can be expressed as

\[ N_{\text{MWCNT}} = N_{\text{MWCNT(periiphery)}} + N_{\text{MWCNT(centre)}} \]  (5)

where \( N_{\text{peri}} \) and \( N_{\text{center}} \) represent the number of CNTs placed in periphery at horizontal and vertical directions, respectively. \( N_{\text{MWCNT(centre)}} \) is calculated using (3) and (4) by replacing the number of CNTs at horizontal and vertical orientations with \( N_{c} \) and \( N_{h} \), respectively. The quantitative values of \( N_{c} \) and \( N_{h} \) are similar to the \( N_{c} \) and \( N_{h} \) as obtained from (4). For different MB and MMB arrangements, the quantitative values of \( N_{c} \) and \( N_{h} \), along with the \( N_{\text{MWCNT}} \) are summarised in Table 1.

2.2 ESC model

This section provides a detailed description of ESC model of bundled MWCNT interconnects that takes into account each transmission line of MWCNTs in parallel. The interconnect parasitics of each transmission line is modelled using the total number of conducting channels associated with MWCNTs in a bundle. The number of conducting channels primarily takes into account the spin and sub-lattice degeneracy of carbon atoms. Naeemi and Meindl [13] modelled the number of conducting channels of each shell in MWCNT as

\[ N(D_i) \approx k_1 D_i + k_2, \quad D_i > d_f/T \]

where \( D_i \) represents the diameter of \( i \)th shell, constants \( k_1 \) and \( k_2 \) have the values of \( 3.87 \times 10^{-3} \) nm \(^{-1}\) K\(^{-1}\) and 0.2, respectively. The thermal energy of electrons and gap between two sub-bands determines the quantitative value of \( d_f \) equivalent to 1300 nm K at room temperature \( (T = 300 \text{ K}) \) [13]. For \( D_i > 4.3 \text{ nm} \), the average number of conducting channels is proportional to its shell diameter. Thus, the total number of conducting channels in an MWCNT can be obtained using the summation of conducting channels \( (N_i) \) of each shell as

\[ N_{\text{channel}} = \sum_{i=1}^{n} N_i \]  (7)

where \( n \) denotes the total number of shells in MWCNT. In a similar way, the total number of conducting channels in an MWCNT bundle can be obtained as

\[ N_{\text{bundle}} = \sum_{i=1}^{N_{\text{MWCNT}}} N_{\text{channel}} \]  (8)

The conduction mechanism of CNTs is ballistic or dissipative because of large mfps in the range of micrometres. The mfp primarily depends on \( D_i \) and can be expressed as [14]

\[ \lambda_{\text{mfp},i} = \frac{10^4 D_i}{(T/T_0) - 2}, \quad T_0 = 100 \text{ K} \]  (9)

Depending on the MTL theory [11, 15], an equivalent RLC model of MWCNT bundle is presented in Fig. 4, which is further simplified to an ESC as shown in Fig. 5. The ESC model of Fig. 5 assumes that all the shells in MWCNT and all the MWCNTs in a bundle are parallel and participate in conduction. The tunnelling

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**Table 1 Number of MWCNTs in different bundle configurations**

| Bundle arrangements | MWCNTs with different number of shells | \( N_{\text{MWCNT}} \) | \( N_{c} \) | \( N_{h} \) |
|--------------------|--------------------------------------|-----------------|--------|--------|
| MB-I               | (MWCNT)\(_{12}\)-shell               | 230             | 9      | 27     |
|                    | (MWCNT)\(_{8}\)-shell               | 0               | 0      | 0      |
|                    | (MWCNT)\(_{4}\)-shell               | 0               | 0      | 0      |
| MB-II              | (MWCNT)\(_{12}\)-shell               | 68              | 5      | 15     |
|                    | (MWCNT)\(_{8}\)-shell               | 0               | 0      | 0      |
|                    | (MWCNT)\(_{4}\)-shell               | 0               | 0      | 0      |
| MB-III             | (MWCNT)\(_{12}\)-shell               | 32              | 5      | 13     |
|                    | (MWCNT)\(_{8}\)-shell               | 0               | 0      | 0      |
|                    | (MWCNT)\(_{4}\)-shell               | 0               | 0      | 0      |
| MMB-I              | (MWCNT)\(_{12}\)-shell               | 127             | 0      | 0      |
|                    | (MWCNT)\(_{8}\)-shell               | 0               | 0      | 0      |
|                    | (MWCNT)\(_{4}\)-shell               | 0               | 0      | 0      |
| MMB-II             | (MWCNT)\(_{12}\)-shell               | 28              | 0      | 0      |
|                    | (MWCNT)\(_{8}\)-shell               | 22              | 4      | 9      |
|                    | (MWCNT)\(_{4}\)-shell               | 27              | 0      | 0      |
|                    | (MWCNT)\(_{8}\)-shell               | 22              | 0      | 0      |
|                    | (MWCNT)\(_{4}\)-shell               | 22              | 4      | 9      |

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**Fig. 4 Equivalent RLC model of MWCNT bundle**
conductance \( (G_i) \) that primarily represents the intershell and inter-CNT electron tunnelling effects has been neglected in the model because of a negligible interaction between two shells in MWCNT [8, 16–18]. For a defect free global interconnect length, Yoon et al. [19] also neglected the electron tunnelling between adjacent shells in MWCNT.

Each MWCNT in bundle demonstrates three types of resistances: (i) quantum or intrinsic resistance \( (R_q) \) that is due to the quantum confinement of electrons in a nano-wire [20], (ii) imperfect metal-nanotube contact resistance \( (R_{mc}) \) that exhibits a typical value of 3.2 kΩ depending on the fabrication process [21] and (iii) scattering resistance \( (R_s) \) that appears because of the static impurity scattering, defects, line edge roughness scattering, acoustic phonon scattering etc. The equivalent resistance of the ESC can be expressed as

\[
R_{ESC} = R_{C,ESC} + R_{ESC}' l
\]

where

\[
R_{C,ESC} = \left[ \frac{1}{(N_{\text{MWCNT}})m_1 \left( 2 \times \sum_{i=1}^{n} N_i + R_{mc} \right)} \right]^{-1} + \cdots + \left[ \frac{1}{(N_{\text{MWCNT}})m_k \left( 2 \times \sum_{i=1}^{n} N_i + R_{mc} \right)} \right]^{-1}
\]

\[
R_{ESC}' = \left[ \frac{1}{(N_{\text{MWCNT}})m_1 \left( 2 \times \sum_{i=1}^{n} N_i + R_{mc} \right)} \right]^{-1} + \cdots + \left[ \frac{1}{(N_{\text{MWCNT}})m_k \left( 2 \times \sum_{i=1}^{n} N_i + R_{mc} \right)} \right]^{-1}
\]

The equivalent capacitance of the ESC can be expressed as

\[
\frac{1}{C_{ESC}} = \frac{1}{C_{Q,ESC}} + \frac{1}{C_{E,ESC}}
\]

where

\[
C_{Q,ESC} = 2C_{Q0} \times N_{\text{total}}, \quad \text{where} \quad C_{Q0} = \frac{2e^2}{\pi \epsilon_0 \eta V_f}
\]

\[
C_{E,ESC} = \frac{2.2 \times 10^5 N_f}{\eta V_f} \times N_f
\]

are presented in Table 1. In addition, each shell in MWCNT and each MWCNT in the bundle experiences an innershell and an inter-CNT coupling capacitance, \( C_s \) and \( C_q \), that primarily depends on the diameter of adjacent shells and centre-to-centre distance between neighbouring CNTs \( (d_{c-c}) \), respectively [8, 23]. The p.u.l. \( C_s \) and \( C_q \) can be expressed as

\[
C_s = \frac{2.2 \times 10^5 N_f}{\eta V_f}
\]

\[
C_q = \frac{2.2 \times 10^5 N_f}{\eta V_f} \left( \frac{d_{c-c}^2}{2} \right)^{-1}
\]

\[
L_{k,ESC} = \frac{L_{k0}}{2N_{\text{total}}}, \quad \text{where} \quad L_{k0} = \frac{h}{2e^2 \eta V_f}
\]

\[
L_{M,ESC} = \frac{\mu_0}{2\pi} \eta \cosh^{-1} \left( \frac{D_n + h_i}{D_n} \right)
\]

3 Capacitively coupled interconnect lines

Crosstalk delays are analysed for different MB and MMB configurations using capacitively coupled interconnect lines as shown in Fig. 6. The interconnect lines in Fig. 6 are modelled by using the ESC of different MB and MMB configurations. The coupled interconnect lines, terminated by a load capacitance \( C_l = 10 \) aF, are connected with a supply voltage \( V_{dd} = 1 \) V. A CMOS driver is used for accurate estimation of crosstalk delay. It can be realised by noting the fact that a transistor in CMOS gate operates partially in linear region and partially in saturation region during switching. However, a transistor can be accurately approximated by a resistor only in the linear region. In the saturation region, the transistor is more accurately modelled as a current source with a parallel high resistance [24, 25]. Using the driver interconnect load (DIL) setup and the ESC model, performance is analysed for different configurations.
bundle configurations at global interconnect lengths ranging from 400 to 2000 μm.

The inter-bundle coupling capacitance ($C_{\text{CM}}$) has a significant effect on crosstalk delay that primarily depends on the spacing between aggressor and victim ($D_p$) [26] and can be expressed as

$$C_{\text{CM}} = \frac{\pi \varepsilon_0 \varepsilon_r}{\cosh^{-1}(S_p/D_m)} \times N_v \tag{19}$$

where $D_m$ is the outershell diameter of MWCNTs facing each other ($N_v$ in Table 1) as shown in Fig. 7. Table 2 summarises the quantitative values of interconnect parasitics associated with different bundle configurations. The quantitative values of these parasitics primarily depend on the bundle arrangement and the number of conducting channels associated with MWCNTs of different numbers of shells.

### 4 Crosstalk analysis

This section analyses propagation delay under the influence of dynamic crosstalk at different input transition times and spacing between coupled interconnect lines. Crosstalk is an important design concern in current nanoscale very large scale integration (VLSI) interconnects that primarily depends on the mutual capacitance, spacing between interconnect lines, relative transition-time skew etc. [26]. Crosstalk (an undesirable noise) is broadly classified into two categories: (i) functional and (ii) dynamic crosstalk. Under the functional crosstalk category, victim line experiences a voltage spike when an aggressor line switches. On the other hand, dynamic crosstalk is observed when aggressor and victim lines switch simultaneously. A change in propagation delay is experienced under dynamic crosstalk when adjacent line (aggressor and victim) switches either in-phase or out-of-phase.

#### 4.1 Crosstalk delay for different transition times

For different transition times and MWCNT bundle configurations, Figs. 8–10 present the out-phase crosstalk delay at global interconnect lengths of 400, 1200 and 2000 μm, respectively. It is observed that the crosstalk delay increases for large transition time that primarily depends on the signal rise and fall time. An increase in rise and fall times also increases the signal propagation delay under the influence of dynamic crosstalk. Apart from this, the percentage reduction in crosstalk delay for different bundle configurations are shown in Tables 3 and 4 at interconnect lengths of 400 and 2000 μm, respectively. It is observed that on using novel MMB-III arrangement, the overall crosstalk delay is reduced by 1.35 times compared with the conventional MB-I. The primary

### Table 2 Equivalent interconnect parasitics for different MB and MMB configurations

| Bundle arrangements | Equivalent resistance | Equivalent inductance | Equivalent capacitance |
|---------------------|-----------------------|-----------------------|------------------------|
|                     | $R_{\text{ESC}}$, Ω   | $L'_{\text{ESC}}$, μH | $C'_{\text{ESC}}$, pF  |
| MB-I                | 3.2                   | 5.21                  | 118.74                 |
| MB-II               | 3.2                   | 4.96                  | 63.79                  |
| MB-III              | 3.2                   | 4.11                  | 56.72                  |
| MMB-I               | 3.2                   | 4.69                  | 95.58                  |
| MMB-II              | 3.2                   | 4.19                  | 61.92                  |
| MMB-III             | 3.2                   | 4.03                  | 50.23                  |

|                     | $R'_{\text{ESC}}$, μΩ | $L'_{\text{ESC}}$, pHμ | $C'_{\text{ESC}}$, fFμ | $C_{\text{CM}}$, fFμ |
|---------------------|-----------------------|------------------------|------------------------|---------------------|
| MB-I                | 13.13                 | 0.04                   | 118.74                 |
| MB-II               | 24.43                 | 0.07                   | 63.79                  |
| MB-III              | 27.48                 | 0.08                   | 56.72                  |
| MMB-I               | 16.30                 | 0.07                   | 95.58                  |
| MMB-II              | 25.16                 | 0.08                   | 61.92                  |
| MMB-III             | 22.19                 | 0.08                   | 50.23                  |

### Table 3 Percentage reduction in crosstalk delay of MMB-III at $l=400\mu m$

| Transition time (ps) | Percentage reduction in crosstalk delay for MMB-III compared with |
|----------------------|---------------------------------------------------------------|
| MB-I                 | MB-II MMB-I MMB-III   |
| 100                  | 100.00 42.86 35.71   |
| 300                  | 52.00 24.24 18.18    |
| 500                  | 48.48 24.00 16.00    |
| 800                  | 42.22 20.00 15.55    |
| 1000                 | 40.38 19.23 15.38    |

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The reason behind this reduction is the lower resistive and capacitive parasitics of novel MMB-III as presented in Table 2. The quantitative values of interconnect parasitics are primarily dependent on the total number of conducting channels that is substantially affected by the diameters of MWCNTs. Interconnect parasitics are considerably reduced for higher MWCNT diameters. Thus, the least parasitics associated with MMB-III results in a lesser crosstalk delay compared with other conventional bundle arrangements.

4.2 Crosstalk delay for different spacings

The spacing between aggressor and victim lines has a significant impact on crosstalk delay as presented in Figs. 11–13 at global interconnect lengths of 400, 1200 and 2000 μm, respectively. It is observed that the crosstalk delay is substantially reduced for an increase in spacing between the aggressor and victim lines. Crosstalk delay, analysed for opposite signal transitions in aggressor and victim lines, is primarily influenced by the coupling capacitance $C_{CM}$. The $C_{CM}$ is mostly affected by the spacing between aggressor and victim as expressed in (19). Irrespective of interconnect lengths, the higher spacing between the coupled lines substanti-
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