CHAPTER 4

ANALYSIS OF NANO STRUCTURE

4.1 INTRODUCTION

Nano Technology is an enabling technology to characterize and manipulate the properties and functionalities of nano structured materials. (Thomas Tsakalakos 2003). A nano tube is a nanometer scale tube-like structure that is formed by different materials like hydrogen, polymers, carbon, copper etc. Among this carbon is frequently used material because the cylindrical carbon molecules have novel properties that make them potentially useful for many applications in electronics, optics and other fields of materials science, as well as potential uses in building architecture. They exhibit extraordinary strength and unique electrical properties, and are efficient conductors of heat (ITRS 2005).

Carbon Nano Tubes (CNTs) are the most studied class of nanotube. A CNT consists of a sheet of graphite rolled up into a tube. They can be single-walled or multi-walled (comprising of multiple concentric cylindrical shells) nanotubes. Depending on the direction in which CNTs are rolled up they demonstrate either metallic or semi-conducting properties (Avouris et al 2003). Semi conducting CNTs are being extensively studied as the future channel material for ultrahigh performance and scaled Field Effect Transistors (FETs) that are expected to be the successors of silicon transistors (Tans et al 1998, Martel et al 1998).
CNTs were first modeled using Littuinger liquid theory at giga hertz frequencies (Burke 2002). An RF circuit model based on the transmission line properties of a carbon nanotube is used to describe the effective electrical properties operating in the frequency range from dc to THz range (Burke 2002). The high frequency circuit model developed have direct applications in Terahertz nanotube transistors, RF nano spintronics and in determining the switching speed of a variety of nanotube based electronic devices (Burke 2003). CNTs for the development of GHz electronic devices has been extensively studied (Burke 2003). Quantitative predictions of the performance of nanotubes as antennas, including the radiation resistance, the input reactance and resistance, and antenna efficiency, as a function of frequency has been reported. Other applications of CNTs include RF transmission line, interconnects, RAM, NEMS switches, sensors and actuators operating in the microwave frequency range. (Wooh et al 2004, Jensen et al 2006, Jang et al 2005, Kaul et al 2006, Ke et al 2005, Dequesnes et al 2002).

4.1.1 Metallic Single Walled CNT

Metallic CNTs have been identified as a possible interconnect material for future Integrated Circuit (IC) technology. Both Single Walled Carbon Nanotubes (SWCNTs) as well as Multiwalled Carbon Nanotubes (MWCNTs) are being investigated as interconnects for performance and scalability. In a metallic MWCNTs, it is difficult to achieve ballistic transport of electrons over long lengths (Schonenberger et al 1999, Bachtold et al 2000). SWCNTs on the other hand have electron mean free paths in the order of a micron which aids for the transport of electrons (McEuen et al 2002). Hence metallic SWCNTs are the preferred candidates for interconnect applications (Hoenlein et al 2004, Ray Chowdhury and Roy 2006). But SWCNT inherently has a large intrinsic resistance which limits its application in high speed interconnects. In the ballistic limit, this resistance is not intrinsic.
to the CNT channel but arises from the metal to nanotube contact at each of the two ends of the nanotube. For perfect contacts and at low bias, the minimum resistance of a CNT interconnect is \( \frac{h}{4e^2} \) where \( h \) is the Planck’s constant and \( e \) is the charge of an electron, which is approximately 6 KΩ. As the CNT interconnect length increases, the associated resistance and the parasitic capacitance also increases. As a result switching delay increases and exceeds the International Technology Roadmap for Semi conductors (ITRS) prediction (Ray chowdhury and Roy 2006). CNT bundles are preferred to reduce the resistance and the associated parasitic capacitance and finally reduce the interconnect delay. Power and thermal/reliability analysis results of CNT bundles as interconnects pave the way for usage in Very Large Scale Integrated circuits (Jun Li et al 2003, Srivastava et al 2005, Srivastava and Baneerjee 2004, Raychowdhury and Roy 2004, Srivastava et al 2005, Naeemi et al 2005). It is shown that the use of CNT bundle vias integrated with copper interconnects can improve copper interconnect lifetime by two orders of magnitude and also reduce optimal global interconnect delay by as much as 30%. (Srivastava et al 2005)

Nano-scale devices, which typically span several orders of magnitude of nano scale in spatial dimensions, have coupled energy domain behavior that is not intuitive. The mechanical behavior of SWCNT has been studied (Tserpes and Papanikos 2005) using finite element method (FEM). The charge distribution on a finite length conductive nano-scale cylinder based on classical electrostatics was done using Boundary element method (BEM) (Changhong et al 2005). An integral formulation for the electrodynamics of metallic carbon nanotubes interconnects based on a fluid model has been proposed (Chiariello et al 2006).A transmission line model describing the propagation along a SWCNT has been derived (Muffucci et al 2008).
Conventional analysis methods such as FEM and BEM for the nano structure involves the generation of sub nano sized meshes, which is a time consuming process and re-meshing is essentially done to optimize the parameters. In nano geometries such as CNT, mesh generation itself is difficult and also the time to obtain convergence increases enormously with the reduction in mesh size. To overcome these difficulties an efficient approach such as mesh-less or mesh-free method has been proposed for numerical solution of partial differential equations corresponding to two or three dimensional nano structures (Aluru 1998, Aluru and Gang Li 2001). Mesh free methods can circumvent the problems of nano scaled meshing and allied convergence problems. This chapter proposes the formulation of the mesh less method using Reproducing Kernel Particle Method (RKPM) to analyze the SWCNT interconnects for RF applications numerically.

4.2 PROBLEM STATEMENT

Under quasi-static approximation, the analysis of CNT structure reduces to that of solving the Laplace’s equation with appropriate boundary and interface conditions. The geometry of the CNT chosen for analysis is shown in Figure 4.1.A metallic single walled CNT of radius \( r \) is placed on the top of dielectric substrate at a height \( h \) above the ground plane. The structure is assumed to have metallic enclosure whose height is approximately ten times that of the substrate thickness. The metallic enclosure would provide mechanical strength, heat sink for active devices and protection against atmosphere.
4.3 MATHEMATICAL FORMULATION

The governing partial differential equation in the domain of interest is given as

\[
\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = 0
\]  

(4.1)

where \( \varphi \) is the potential distribution. In the analysis, to impose the boundary conditions the geometry is divided into 6 regions with 10 boundaries separating the regions from one another as in Figure 4.2.
The boundary conditions are

**Region 1** \((0 < x < a \& 0 < y < e)\)

(i) \(\varphi_1 = 0 \at x = 0 \& 0 < y < e\) (Metallic enclosure)

(ii) \(\varphi_1 = 0 \at y = 0 \& 0 < x < a\) (Metallic enclosure)

(iii) \(\frac{\partial \varphi_1}{\partial y} = \frac{\partial \varphi_6}{\partial y} \at y = e \& 0 \leq x \leq a\)

(interface between substrate and air) \((4.2)\)

**Region 2** \((a < x < b \& 0 < y < e)\)

(iv) \(\varphi_2 = 0 \at y = 0 \& a < x < b\) (Metallic enclosure)

(v) \(\varphi_2 = 1 \at y = e - \sqrt{2cx - g^2 - x^2 - c^2} \& a < x < b\)

(On nano tube) \((4.3)\)

**Region 3** \((b < x < d \& 0 < y < e)\)

(vi) \(\varphi_3 = 0 \at y = 0 \& b < x < d\) (Metallic enclosure)

(vii) \(\varphi_3 = 0 \at x = d \& 0 < y < e\) (Metallic enclosure)

(viii) \(\frac{\partial \varphi_3}{\partial y} = \frac{\partial \varphi_4}{\partial y} \at y = e \& b < x < d\)

(interface between substrate and air) \((4.4)\)

**Region 4** \((b < x < d \& e < y < f)\)

(ix) \(\varphi_4 = 0 \at y = f \& b < x < d\) (Metallic enclosure)

(x) \(\varphi_4 = 0 \at x = d \& e < y < f\) (Metallic enclosure)

(xi) \(\frac{\partial \varphi_3}{\partial y} = \frac{\partial \varphi_4}{\partial y} \at y = e \& b < x < d\)

(interface between substrate and air) \((4.5)\)
Region 5 \((a < x < b \& e < y < f)\)

(xii) \(\varphi_5 = 0 \text{ at } y = f \& a < x < b\) \hspace{1cm} \text{(Metallic enclosure)}

(xiii) \(\varphi_5 = 1 \text{ at } y = e + \sqrt{2cx - g^2 - c^2 - x^2} \text{ and } a < x < d\)

\hspace{1cm} \text{(On nano tube)} \hspace{1cm} (4.6)

Region 6 \((0 < x < a \& e < y < f)\)

(xiv) \(\varphi_6 = 0 \text{ at } x = 0 \& e < y < f\) \hspace{1cm} \text{(Metallic enclosure)}

(xv) \(\varphi_6 = 0 \text{ at } y = f \& 0 < x < a\) \hspace{1cm} \text{(Metallic enclosure)}

(xvi) \(\frac{\partial \varphi_1}{\partial y} = \frac{\partial \varphi_6}{\partial y} \text{ at } y = e \& 0 < x < a\)

\hspace{1cm} \text{(Interface between substrate and air)} \hspace{1cm} (4.7)

The interface conditions are

Region between 1 and 2
\(\varphi_1 = \varphi_2 \text{ at } x = a \& 0 < y < e\)

Region between 2 and 3
\(\varphi_2 = \varphi_3 \text{ at } x = b \& 0 < y < e\) \hspace{1cm} (4.8)

Region between 4 and 5
\(\text{at } x = b \& e < y < f\)

Region between 5 and 6
\(\varphi_5 = \varphi_6 \text{ at } x = a \& e < y < f\)

4.3.1 RKPM Formulation

Considering the electrostatic problem, namely CNT structure analysis it is regarded as that of constructing a solution surface \(\varphi(x, y)\) over a
specified region in the x-y plane, so as to satisfy the boundary and interface conditions. The approximate potential solution for the domain can be written as (Liu et al 1995, Liu et al 1995, Chen et al 1996).

\[ \varphi^a(x, y) = \sum_{i=1}^{NP} \overline{w}_d(x - x_i, y - y_i) \varphi(x_i, y_i) \Delta V_i \]  

(4.9)

\( \varphi(x_i, y_i) \) is the value of the function \( \varphi \) at node \((x_i, y_i)\) and \( \overline{w}_d(x - x_i, y - y_i) \) is the corrected kernel function, which is given as

\[ \overline{w}_d(x - x_i, y - y_i) = C(x - x_i, y - y_i) w_d(x - x_i, y - y_i) \]  

(4.10)

where \( C(x - x_i, y - y_i) \) is the correction function and \( w_d(x - x_i, y - y_i) \) is the kernel function. The correction function for the chosen problem is given as

\[ c(x - x_i, y - y_i) = c_0 + c_1 (x - x_i) + c_2 (y - y_i) + c_3 (x - x_i) (y - y_i) \]  

(4.11)

where \( c_0, c_1, \ldots, c_5 \) are the unknown correction function coefficients. A cubic spline kernel function is used for RKPM analysis as discussed in Chapter 2. Equation (4.9) can be rewritten compactly as

\[ \varphi^a(x, y) = \sum_{i=1}^{NP} N_i(x, y) \varphi(x_i, y_i) \]  

(4.12)

where \( N_i(x, y) \) is the RKPM shape function for node \( I \). The shape function for particle \( I \) can then be written as

\[ N_i(x, y) = C(x - x_i, y - y_i) w_d(x - x_i, y - y_i) \]  

(4.13)
In matrix form equation (4.12) can be written as

\[
\begin{pmatrix}
\Phi(x_1) \\
\vdots \\
\Phi(x_m) \\
\Phi(x_{m+l})
\end{pmatrix} = \begin{pmatrix}
N_1(x_1) & \ldots & N_m(x_1) \\
N_1(x_{m+l}) & \ldots & N_m(x_{m+l}) \\
N_1(x_{m+2l}) & \ldots & N_m(x_{m+2l}) \\
N_1(x_{m+3l}) & \ldots & N_m(x_{m+3l})
\end{pmatrix} \begin{pmatrix}
\Phi_1 \\
\vdots \\
\Phi_m \\
\Phi_{m+l}
\end{pmatrix}
\]

(4.14)

Solving the system of equations (4.14), results in the scalar potentials at each point, which in turn gives the electrostatic capacitance and the line parameter namely characteristic impedance of CNT under consideration. The characteristic impedance of the CNT is calculated using

\[
Z_c = \sqrt{(L_K + L_M) \left( \frac{1}{C_Q} + \frac{1}{C_{ES}} \right)}
\]

(4.15)

where \(L_K\) is the Kinetic inductance, \(L_M\) is the Magnetic inductance, \(C_Q\) is the Quantum capacitance, \(C_{ES}\) is the Electrostatic Capacitance. Since electrostatic capacitance is dependent on the radius of the tube, by varying the radius of the nano tube from 1nm to 3nm the variation in characteristic impedance and the electrostatic capacitance can be found out. A comparison of the present formulation is done with the Littuinger liquid theory model available in (Burke 2002).

4.3.2 Equivalent Circuit Model of CNT/CNT Bundles

To show the correctness of the proposed RKPM analysis procedure an equivalent circuit model for single walled carbon nanotube proposed in
(Burke 2002) is used. The electrostatic capacitance ($C_{ES}$) found using RKPM procedure is used in the equivalent circuit model.

![Equivalent circuit for a nano transmission line](image)

**Figure 4.3 Equivalent circuit for a nano transmission line**

![Isolated conductor with diameter d over a ground plane at a height h](image)

**Figure 4.4 Isolated conductor with diameter d over a ground plane at a height h**

The electrostatic capacitance ($C_{ES}$) is calculated by treating the CNT as a thin wire, with diameter $d$, placed a distance $h$ away from a ground plane as in Figure 4.4. The quantum capacitance ($C_Q$) accounts for the quantum electrostatic energy stored in the nanotube when it carries current. The inductance associated with an isolated SWCNT can be calculated from the magnetic field of an isolated current carrying wire some distance away
from a ground plane. Using the standard formulas (4.15-4.17) the equivalent circuit component values are calculated. The Kinetic inductance per unit length is given as

\[ L_{\text{kinetic}} = \frac{h}{2e^2V_F} \]  

(4.16)

where \( h \) is the Planck’s constant, \( e \) is the charge of the electron, \( V_F \) is the Fermi velocity of graphene.

The magnetic inductance per unit length is given

\[ L_{\text{magnetic}} = \frac{\mu}{2\pi} \cosh^{-1}\left(\frac{2h}{d}\right) \]  

(4.17)

where \( h \) is the distance between ground plane and CNT, and \( d \) is the diameter of the tube, \( \mu \) is the permeability. The Quantum capacitance is given as

\[ C_Q = \frac{2e^2}{hV_F} \]  

(4.18)

where \( h \) is the Planck’s constant, \( e \) is the charge of the electron, \( V_F \) is the Fermi velocity of graphene. To overcome the drawbacks of Single walled CNT, a bundle of CNTs are considered for interconnect applications.

The high current density of CNT bundles would facilitate the reduction of the effective resistance and delay in an interconnect.
A CNT-bundle is assumed to be composed of hexagonally packed identical metallic single-walled carbon nanotubes. Each CNT is surrounded by six immediate neighbors, their centers uniformly separated by a distance ‘x’. The densely packed structure with ‘x’ = ‘d’ (CNT diameter) is shown in Figure 4.5, will lead to best interconnect performance. The equivalent circuit for CNT bundle is represented in Figure 4.6. The expressions to calculate the number of CNTs in the bundle are given in equation (4.19), where \( n_w \) is the number of “rows” in the interconnect bundle, \( n_w \) is the number of “columns”, \( n_{CNT} \) is the total number of CNTs where \( H \) is the height of the bundle as \((2W)\) and \( W \) is the width of the bundle.

\[
\begin{align*}
n_w &= \left\lfloor \frac{w - d}{x} \right\rfloor \\
n_H &= \left\lfloor \frac{h - d}{(\sqrt{3}/2)x} \right\rfloor + 1 \\
n_{CNT} &= n_w n_H - \frac{n_H}{2}, \text{ if } n_H \text{ is even} \\
&= n_w n_H - \frac{n_H - 1}{2}, \text{ if } n_H \text{ is odd}
\end{align*}
\]
Resistance of a CNT Bundle

In order to calculate the effective resistance of a CNT bundle, it is assumed that all CNTs packed into the interconnect structure are metallic and conducting. Since it is difficult to control the conductance properties of all CNTs in the bundle reduced packing densities can be considered as shown in Figure 4.5. The CNT-bundle resistance is then given by

$$R_{bundle} = \frac{R_{isolated}}{n_{CNT}}$$  \hspace{1cm} (4.20)

Capacitance of a CNT-Bundle

In the electrostatic analysis of a CNT bundle, each CNT is treated as a classical metal with equal potential over the tube. The expression for the electrostatic capacitance ($C_E$) for an isolated CNT has been given as

$$C_E^{bundle} = 2C_{En} + \frac{n_w - 2}{2} C_{Ef} + \frac{3(n_H - 2)}{5} C_{En}$$  \hspace{1cm} (4.21)
where

\[ c_{En} = \frac{2\pi \varepsilon}{\ln \left( \frac{w}{d} \right)} \quad \text{and} \quad c_{Ef} = \frac{2\pi \varepsilon}{\ln \left( \frac{2w}{d} \right)} \]

where \( c_{En}, c_{Ef} \) are parallel plate capacitances of isolated CNT with respect to near and far interconnects respectively.

The quantum capacitances of all the CNTs forming a CNT bundle appear in parallel, the effective quantum capacitance of the bundle is the sum of the individual quantum capacitances. It can be expressed as

\[ c_Q^{\text{bundle}} = c_Q^{\text{CNT}} \ast n_{\text{CNT}} \quad (4.22) \]

where \( C_Q^{\text{CNT}} \) is the quantum capacitance of an isolated CNT and \( n_{\text{CNT}} \) is the total number of CNTs forming the bundle.

**Inductance of a CNT-Bundle**

The inductance of a CNT bundle is given by the parallel combination of the inductances corresponding to each CNT forming the bundle and can be given as

\[ L_{\text{bundle}} = \frac{L_{\text{CNT}}}{n_{\text{CNT}}} \quad (4.23) \]

where \( L_{\text{CNT}} \) is the inductance of an isolated SWCNT.
Propagation time delay of single carbon nanotube placed on a substrate can be expressed as

$$\tau = 0.7 R_{tr} C_L + \frac{L}{\sqrt{2} V_F}$$  \hspace{1cm} (4.24)

$R_{tr}$ is driver resistance (equal to line characteristic impedance for impedance matching), $C_L$ is load capacitance and $L$ is interconnect length, $V_F$ is wave speed.

Propagation time delay for copper interconnects can be expressed as

$$\tau = 0.7 R_{tr} C_L + 0.7(r_{in} C_L + c_{in} R_{tr})L + 0.4 r_{in} c_{in} L^2$$  \hspace{1cm} (4.25)

Propagation time delay of carbon nano tube bundle is given as

$$\tau_{bundle} = R_{tr} (c_{bundle} L + C_L)$$  \hspace{1cm} (4.26)

where $C_{bundle}$ is capacitance per unit length of the bundle of nanotubes, assuming that $c_{bundle} \approx c_{in}$, the ratio of nanotube bundles and copper wires can be written as

$$\frac{\tau_{copper}}{\tau_{Bundle}} = 1 + \frac{C_L}{C_{in} L} \frac{r_{in} L}{r_{tr}} \approx 1 + \frac{r_{in} L}{R_{tr}}$$  \hspace{1cm} (4.27)

### 4.4 RESULTS AND DISCUSSIONS

#### 4.4.1 Electro-Static Performance

To show the validity of the present method of analysis, computations are carried out for the carbon nano tube on a silicon dioxide substrate, with nanotube length ($L$) as 100 µm, height of the tube above the
substrate \((h)\) as 75nm and the radius of the tube is varied from 1nm to 3nm. For comparison purpose the dimensions of the CNT are taken. The software code for the analysis procedure has been written in Matlab platform. The device is simulated using 61 scattered points. The solution to the governing equation (4.1) along with the boundary conditions (4.2- 4.8) is obtained in the form of potentials. Once the potentials are known the electro static capacitance and the impedance of the CNT as a function of the radius\((r)\) of the tube are calculated using the standard formulas (4.16 - 4.18). The variation of characteristic impedance and the electrostatic capacitance with respect to various radius of the nano tube are presented in Figures 4.7(a) and 4.7(b). The values of characteristic impedance and electrostatic capacitance calculated agrees well with the already reported data by Burke using Littuinger liquid theory model as shown in Figure 4.7(a) and 4.7(b).

![Graph showing variation of electrostatic capacitance w.r.t radius of CNT](image)

**Figure 4.7 (a) Electrostatic capacitance \((C_{ES})\) for different radius \((r)\)**
The minor discrepancies of about 2% error in the electrostatics capacitance obtained through RKPM formulation can be reduced further by using higher order polynomials. The electrostatic capacitance found out using the RKPM method is used in the equivalent circuit of CNT interconnects (Srivastava and Baneerjee 2005) to obtain the RF performance.

4.4.2 Radio Frequency Performance

The radio frequency performance of the SWCNT as interconnect for RF applications is obtained using the commercial electromagnetic simulator Agilent ADS. Using the transmission line model available in (Burke 2003) the component values per unit length are calculated. The electrostatic capacitance ($C_{ES}$) found out using the RKPM method is used in the equivalent circuit model of CNT interconnects to obtain the RF performance. Figure 4.8 presents the variation of scattering parameters with respect to frequency as a function of the static capacitance found using the proposed method and
Littuinger liquid theory. The validity of the proposed approach is carried out by comparing the value of $S_{21}$ for RKPM and LLT method as in figure 4.8. Simulation results in a return loss of -5.24dB for RKPM and -5.23dB for LLT and the transmission coefficient is almost negligible at a frequency of 400GHz. It shows that the proposed method provides accurate results up to Terahertz range.

![Figure 4.8 Simulated magnitude of $S_{11}$ and $S_{21}$ obtained using equivalent circuit model for CNT interconnect with electrostatic capacitance ($C_{ES}$) obtained using RKPM and LLT](image)

Figure 4.8 shows the frequency behavior of $S_{11}$ for SWCNT and for a classical Cu interconnects. The values of the equivalent circuit parameters for an SWCNT and copper interconnects calculated using the formulas are $L_K = 16\,\text{pH/µm}$, $C_{ES}=50\,\text{aF/µm}$, $C_Q=100\,\text{aF/µm}$, $d=2\,\text{nm}$, $h=75\,\text{nm}$, Length of CNT $=100\,\text{µm}$, $L=35\,\text{fH/µm}$, $C=977\,\text{aF/µm}$. Simulation results in return loss...
(S_{11}) of -5.25 dB and -24.38 dB for CNT and Cu at a frequency of 400 GHz. The transmission loss $S_{21}$ is almost negligible.

From figure 4.9 the amount of power loss can be calculated from the obtained scattering parameters using $S_{11} = -10 \log(x)$. The percentage of power lost in SWCNT is more (29%) compared to copper interconnects (0.35%). The propagation delay along the SWCNT and copper interconnects can be calculated using the formulas (4.24-4.27) and it is more in single CNT (2.75 ps) due to high contact resistance. To make the CNT interconnect suitable for gigahertz applications, a bundle of CNTs are used instead of SWCNT as in Figure 4.6 to reduce the inherent drawbacks namely the propagation delay and power loss.
Figure 4.10 presents the variation of the scattering parameters as a function of frequency for single CNT and bundle of CNT. The bundle has a width \((w)\) of 20nm, height of the bundle \((h)\) as \(2w\), number of nanotubes are 851 and the corresponding equivalent circuit parameters calculated using the formulas (4.20-4.23) are \(L_{\text{bundle}} = 16.8\text{pH/µm}\), \(C_{Q\text{bundle}} = 85.1\text{fF/µm}\), \(C_{E\text{bundle}} = 2.948\text{fF/µm}\). The simulated RF performance in Figure 4.10 shows that the return loss is about -10.60dB at a frequency 400GHZ which is better compared to Single CNT (-5.25dB). The amount of power lost in CNT bundle is reduced from 29% to 8.67% and the delay also gets reduced to 1.2 ps from 2.3 ps compared to the single carbon nano tube.

![Figure 4.10 Simulated magnitude of \(S_{11}\) and \(S_{21}\) of bundle CNT interconnects with \(L_{\text{bundle}} = 16.8\text{pH/µm}\), \(C_{Q\text{bundle}} = 85.1\text{fF/µm}\), \(C_{E\text{bundle}} = 2.948\text{fF/µm}\) over the frequency range 1 to 500 GHz](image)

Table 4.1 gives the details of the calculated equivalent circuit parameters for single CNT, Single copper and CNT bundles and shows the possible delay reduction in using CNT bundles for RF interconnect applications.
Table 4.1 Comparison between Single carbon, copper and Bundle CNT

<table>
<thead>
<tr>
<th>Type of Line</th>
<th>Dimensions</th>
<th>Equivalent circuit parameters</th>
<th>$S_{11}$(dB) (at 400GHz)</th>
<th>Power loss (%)</th>
<th>Delay(ps) for (L=100µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single carbon</td>
<td>$h=75$nm, $d=2$nm</td>
<td>$L_r=16nH/\mu m$ $L_s=1pH/\mu m$ $C_p=100aF/\mu m$ $C_e=50aF/\mu m$</td>
<td>-5.25</td>
<td>29</td>
<td>2.75</td>
</tr>
<tr>
<td>Single copper</td>
<td>$h=75$nm, $W=80$nm</td>
<td>$L=35fH/\mu m$ $C=977aF/\mu m$</td>
<td>-24.6</td>
<td>0.35</td>
<td>2.3</td>
</tr>
<tr>
<td>Carbon bundle (W=20nm)</td>
<td>$h=2W$, $n_{CNT}=851$</td>
<td>$L_{Q}=18.8pH/\mu m$ $C_p=85.1fF/\mu m$ $C_e=2.948fF/\mu m$</td>
<td>-10.626</td>
<td>8.657</td>
<td>1.2</td>
</tr>
</tbody>
</table>

4.5 CONCLUSION

In this chapter mesh-less analysis of carbon nanotube based on Reproducing Kernel Particle method is presented. The line parameters namely electrostatic capacitance and the characteristic impedance are evaluated with respect to physical parameters namely nanotube diameter. The proposed approach is validated by comparing the results with Littuinger Liquid theory model. Electrostatic capacitance obtained through RKPM is used in the equivalent circuit of CNT to obtain the radio frequency performance. Single Copper and single CNT are compared in terms of scattering parameters and delay at a frequency of 400GHz. The amount of power lost and delay is more in single CNT due to the presence of high resistance. To reduce the resistance and delay and to improve the performance CNT bundles are used. Radio frequency performance of the single CNT and CNT bundles (with 851 CNTs) are obtained using ADS. The amount of power lost is 8.67% only and the delay is also reduced to 1.2 ps which are less compared to the single carbon nano tube. The simulation result shows that the interconnect behaves well upto terahertz frequencies and reveals the possibility of CNT application in wireless designs.