1-1-2017

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Yaseen Jurn
University Malaysia Perlis

MohamedFareq AbdulMalek
University of Wollongong in Dubai

Hasliza Rahim
University Malaysia Perlis

Sawsen Mahmood
University of Mustansiriyah

Wei Liu
University Malaysia Perlis, wliu@ustc.edu.cn

Electromagnetic Modelling of Bundle of Single-walled Carbon Nanotubes with Circular Geometry for Antenna Applications

Yaseen N. Jurn [1,2], Mohamedfareq Abdulmalek [3], Hasliza A. Rahim [4], Sawsen A. Mahmood [5], and Wei-Wen Liu [6]

[1] School of Computer and Communication Engineering
University Malaysia Perlis (UniMAP), 02000 Arau, Perlis, Malaysia
yaseen_nasir@yahoo.com

[2] Minister of Science and Technology, Baghdad, Iraq

[3] Faculty of Engineering and Information Sciences
University of Wollongong in Dubai (UOWD), Dubai, United Arab Emirates
mohamedfareqmalek@uowdubai.ac.ae

[4] Bioelectromagnetics Research Group (BioEM), School of Computer and Communication Engineering
University Malaysia Perlis (UniMAP), Pauh Putra, Arau, Perlis 02600, Malaysia
hrahim3@gmail.com

[5] Computer Science Department, College of Education
University of Mustansiriyah, Baghdad, Iraq
mahmood_sawsan@yahoo.com

[6] Institute of Nano Electronic Engineering
University Malaysia Perlis (UniMAP), 01000 Kangar, Perlis, Malaysia
vwenliu@yahoo.com

***Abstract* ─** This paper aims to present an effective electromagnetic (EM) modelling approach for circular bundle of single-walled carbon nanotubes (CB-SWCNTs), based on the electrical conductivity, relative complex permittivity and linear distribution impedance by applying General Ohm's law for this bundle. The equivalent single conductor material (ESCM) model for personification the CB-SWCNTs is presented in this paper. The main target of this modelling approach is to estimate and investigate the EM properties of CB-SWCNTs using common EM engineering tool solver CST (MWS). For this purpose, the CB-SWCNTs and ESCM dipole antennas will be designed and implemented using CST (MWS). Mathematically, the equivalent conductivity model, relative complex permittivity and other parameters of the CB-SWCNTs will be derived in this paper and considered as equivalent material parameters for the ESCM. This modelling technique is expected to provide new avenues for designing different antenna structures.

***Index Terms* ─** Bundle of SWCNTs, CB-SWCNTs, CB-SWCNTs dipole antenna, CNTs dipole antenna, nano-dipole antenna.

I. INTRODUCTION

In recent years, the carbon nanotubes composite (CNTs-composite) have been an efficient candidate material for different applications due to their unique electrical and physical properties. However, the CNTs-composite material is still at the forefront of research today. It is also considered as promising material for nano-scale applications.

The essential investigations of the CNTs antenna model have been conducted by many researchers using different comprehensive techniques [1-8]. A lot of research had been presented by Hanson et al. [9-15], in order to investigate and study the fundamental electrical properties as well as the EM behavior of the SWCNT dipole antenna. In the context of these studies, in [6] Hanson provided an equivalent model for SWCNT using a common solid conducting material as nanowire, which will be adopted in this work to present the simple equivalent modelling approach for the SWCNT in the

Submitted On: May 4, 2016
Accepted On: February 6, 2017

CST (MWS).

The bundle of SWCNTs (B-SWCNTs) structure was proposed by many researchers instead of individual SWCNT to mitigate the problems related to the SWCNT-dipole. Therefore, several studies used the circuit modelling technique for modelling the B-SWCNTs, in order to investigate its electrical and EM properties with different cross-sectional area (rectangular and circular cross-section) [17-25]. For this purpose, the B-SWCNTs dipole antenna configuration was utilized by many researchers to investigate the EM properties of B-SWCNTs [26-30]. Previous research was implemented B-SWCNTs dipole antenna using an equivalent circuit modelling approach and numerical mathematical approach. In contrast, it is very difficult to implement these modelling approaches in the available EM engineering tool solver.

The most important issue of the nanotechnology devices was represented by conducting a communication between the devices themselves and the outside world. For this reason, this work presents an attempt to get benefits from the advantages of the CB-SWCNTs properties to mitigate this issue by designing nano-antennas. Therefore, the estimation of the EM behavior of CB-SWCNTs with several cross-sectional areas through available EM engineering software package is a significant matter. Therefore, this paper presents equivalent modelling approach (ESCM) for the bundle of SWCNTs with a circular cross-sectional area (CB-SWCNTs). As well as, the simple modelling approach for the SWCNT is presented for the purpose of design the multi conductors CB-SWCNTs. These modelling approaches will be utilized to exhibit the EM properties of the CB-SWCNTs structure and to validate the equivalent modelling approach of CB-SWCNTs. The equivalent single conductor material model (ESCM) is proposed to personification the CB-SWCNTs, based on applying the electrical conductivity, relative complex permittivity, linear distribution impedance, and General Ohm's law. Also, the nano-solid tube material model (NSTM) is utilized to represent the SWCNT by applying the same rules and conditions. The purpose of ESCM modelling approach is to investigation and prediction the EM properties of this bundle with different numbers of SWCNTs. To validate this modelling approach, the dipole antenna configuration of multi conductors CB-SWCNTs based on NSTM model and the corresponding ESCM model will be designed and implemented in the CST (MWS). The comprehensive performance comparisons between the ESCM modelling approach results and the results of related corresponding works will be performed. Finally, the matching input impedance issue of SWCNT dipole antenna and CB-SWCNTs dipole antenna is discussed.

II. FRAMEWORK

For the purpose of EM modelling of CB-SWCNTs, the progress of this framework is presented as follows: First, explain the general configuration of CB-SWCNTs. Second, the CB-SWCNTs is represented by an equivalent single conductor material (ESCM) model and then implemented in the CST (MWS) with a circular cross-sectional area by inserting the material parameters of CB-SWCNTs into CST (MWS). A mathematical analysis related to an equivalent complex conductivity, complex permittivity and other important parameters of the CB-SWCNTs is presented in this work. Third, the nanoscale solid tube material model (NSTM) which is an equivalent to the SWCNT is presented to design the multi conductors CB-SWCNTsdipole antenna. Finally, the ESCM dipole antenna is utilized to predict the EM properties of CB-SWCNTs structure in different geometrical size and dimensions.

A. Configuration of CB-SWCNTs

The CB-SWCNTs is constructed of several identical numbers (*N*) of armchair-SWCNTs which has a radius (*r*), which are arranged in parallel and aligned along the axis of bundle. The number of SWCNTs in this bundle depends on its circular cross-sectional area. Figure 1 shows the sketch of CB-SWCNTs.

This configuration is presented in this work based on neglecting the effects of wrapping and twisting of the SWCNTs in the bundle by assuming that all SWCNTs are parallel aligned along the same axis [31]. In addition, the electron transport along individual SWCNT is slightly affected by the nearest SWCNTs in the bundle because the inter-tube conductance is slightly compared to the conductance along the SWCNT [32].

In this configuration, the cross-section specific area of CB-SWCNTs is calculated as a function of their characteristics (radius of SWCNT *r*, lattice constant Δ, and number of SWCNTs in the bundle *N*) and vice versa:

$$R_B = r + (2r + \Delta)(N_x - 1). \quad (1)$$

Due to the hexagonal geometric structure of this bundle, the total number (*N*) of SWCNTs included in the bundle depending on the number of outer side SWCNTs (*Nx*) that forms the outer side of the hexagonal structure. Where, the radius of CB-SWCNTs (R_B) represents the radius of the ESCM model:

$$N_x = \left(\frac{R_B - r}{(2r + \Delta)} \right) + 1, \quad (2)$$

$$N = 1 + \sum_{j=2}^{N_x} 6\,(j-1). \quad (3)$$

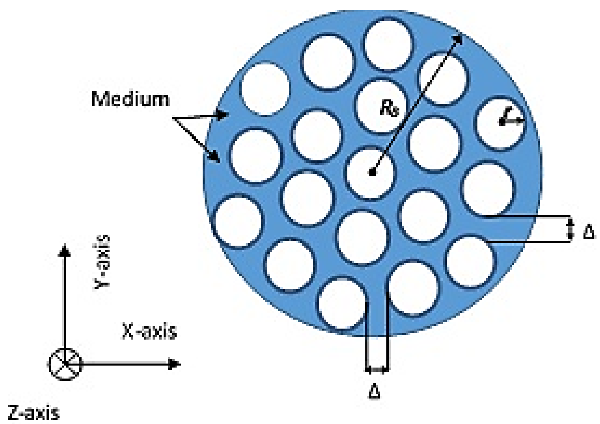

Fig. 1. Cross section of CB-SWCNTs with equivalent radius (R_B) and identical SWCNTs with radius (r).

B. Mathematical analysis of CB-SWCNTs

In this section, the key material parameters of CB-SWCNTs are derived based on the mathematical analysis of this bundle. The effective conductivity model of the CB-SWCNTs is derived mathematically for the purpose of simulation and modelling approach. The equivalent conductivity model of the CB-SWCNTs is represented by a general form bellow:

$$\sigma_{bundle} = \sigma_{scalar}\ I = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{bmatrix}. \quad (4)$$

Where (I) is the identity matrix, (σ_{bundle}) is the effective complex conductivity model of CB-SWCNTs and (σ_{scalar}) is the scalar function consist of different components of the conductivity with different directions (x, y, and z-direction). When the bundle is oriented along the z-direction, therefore, the main component of the conductivity is the (σ_z); whereas the other components (σ_x and σ_y) are not taken into account in this work. The embedded medium of this bundle which is assumed has a very small conductivity ($\sigma_{\mathrm{med}} \cong 0$) or ideal dielectric medium. Therefore, at $\sigma_{bundle} >> \sigma_{med}$, $\sigma_{\mathrm{med}} \cong 0$ and $\sigma_x = \sigma_y = 0$, the conductivity of the bundle is deduced as shown below:

$$\sigma_{bundle} = \sum_{j=1}^{k} m_j \sigma_{zj}. \quad (5)$$

Where, k is the number of materials constructed the bundle and m_j is the volume fraction factor of the material. In this work, the number of materials is two (which are SWCNTs and dielectric material of the medium). Therefore, the mentioned Equation (5) is given by the general formula below:

$$\sigma_{bundle} = \sum_{j=1}^{2} m_j \sigma_{zj} = m_1 \sigma_{z1} + m_2\ \sigma_{z2}. \quad (6)$$

Where, (σ_{z1}) is the conductivity of SWCNTs (σ_{SWCNT}), and (σ_{z2}) is the conductivity of the imbedded material (dielectric medium).

$$\sigma_{bundle} = m_1 \sigma_{SWCNT} + m_2\ \sigma_{med}. \quad (7)$$

At $\sigma_{\mathrm{med}} \cong 0$, the conductivity of the CB-SWCNTs is deduced by this formula:

$$\sigma_{bundle} = \sigma_{SWCNT} \frac{N\ A_{SWCNT}}{A_B}. \quad (8)$$

Where A_{SWCNT} is a cross-sectional area of the individual SWCNT (circumference of the SWCNT), and A_B is the cross-sectional area of the bundle. The formula mentioned in Equation (8), can be utilized with bundle has (circular or rectangular) cross-sectional area. From the relation between the two areas of SWCNT and CB-SWCNTs (A_{SWCNT} and A_B) the volume fraction V_{FR} for this structure is represented by the form ($V_{FR} = \frac{N\ A_{SWCNT}}{A_B}$).

Then, this leads to:

$$\sigma_{bundle} = \sigma_{SWCNT} \frac{2r\ N}{R_B^2}. \quad (9)$$

Based on the conductivity of the SWCNT presented in [9], the Equation (9) is given by the form below:

$$\sigma_{bundle} = -j \frac{4Ne^2V_f}{\pi^2 R_B^2 h(w - jv)}. \quad (10)$$

Where, e is the electron charge, h is the reduced Plank's constant ($h = 1.05457266 \times 10^{-34}\ J.s$), V_f is the Fermi velocity of CNT ($V_f = 9.71 \times 10^5$ m/s), v is a phenomenological relaxation frequency of SWCNT ($v = 6T/r$), so, $F_v = v/2\pi$, where (T=300) is temperature in kelvin, and w is the angular frequency.

From Equation (10), the complex conductivity of the bundle depends on the number of SWCNTs and the cross-sectional area of the bundle. Hence, this conductivity represents the equivalent conductivity of the ESCM model:

$$\sigma_{bundle} = \sigma_{ESCM}. \quad (11)$$

In addition to the effective conductivity model of the CB-SWCNTs structure, the plasma frequency is considered as a remarkable parameter for the EM modelling and simulation of the CB-SWCNTs structure in different 3D EM simulation software package for antenna applications. On the bases of the effective conductivity model mentioned in Equation (10) and the bulk conductivity model presented by Hanson [9], the plasma frequency (w_{PB}) of the CB-SWCNTs and ESCM model is deduced as follows:

$$w_{PB} = \frac{2e}{\pi R_B}\sqrt{\frac{N_{eq,B}\ V_f}{\varepsilon^o h}}\ . \qquad (12)$$

Where $N_{eq,B} = \left(\frac{4Nm_e V_f}{\pi^2 R_B r^2}\right)$ is the number of electrons per unit volume of the bundle; also, the phenomenological relaxation frequency (v_B) of the CB-SWCNTs is given by this formula below:

$$v_B = \frac{6T}{R_B}\ . \qquad (13)$$

On the other hand, the real part ($\varepsilon_B^{'}$) and imaginary part ($\varepsilon_B^{"}$) of the relative complex permittivity of CB-SWCNTs (ε_B) are concluded based on the plasma frequency

$$\varepsilon_B^{'} = 1 - \frac{w_{PB}^2}{w^2 + v_B^2} \qquad (14)$$

$$\varepsilon_B^{"} = \frac{w_{PB}^2 v_B}{w^3 + w v_B^2} \qquad (15)$$

In another context, according to the general admitted definition of the complex permittivity demonstrated in the previous research [33], the permittivity and conductivity of CB-SWCNTs are linked by the following relation

$$\varepsilon_B = 1 + \frac{\sigma_{bundle,i}}{w\varepsilon^o} - j\frac{\sigma_{bundle,r}}{w\varepsilon^o}, \qquad (16)$$

$$\varepsilon_B^{'} = 1 + \frac{\sigma_{bundle,i}}{w\varepsilon^o}, \qquad (17)$$

$$\varepsilon_B^{"} = \frac{\sigma_{bundle,r}}{w\varepsilon^o}. \qquad (18)$$

As a result, the relative complex permittivity of CB-SWCNTs is modeled with Equations (14 and 15) or Equations (17 and 18), the both equation sets provide the same results. Therefore, the EM parameters of CB-SWCNTs which are extracted (or estimated) in this work is utilized to represent this composite material in the different 3D EM simulation software packages including CST (MWS) and HFSS and other.

C. Modelling approach of CB-SWCNTs

The material parameters of CB-SWCNTs extracted in the mathematical analysis above are make to possible to represent the CB-SWCNTs by an equivalent single conductor material model (ESCM) through CST (MWS). This modelling approach contributes to investigate the EM behavior of this bundle with different geometrical structures. Therefore, by inserting the material parameters of CB-SWCNTs into the CST (MWS) software package, the ESCM model can be designed and implemented. For the purpose of modelling approach, the schematic of the ESCM model is an equivalent to the CB-SWCNTs Fig. 2. The dipole antenna for both CB-SWCNTs and ESCM was employed to validate this modelling approach depending on the comparison between their results.

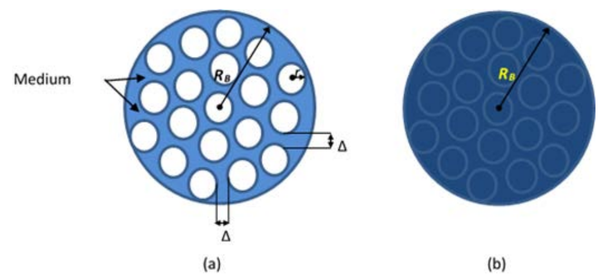

Fig. 2. Schematic configuration of: (a) CB-SWCNT and (b) equivalent ESCM model.

D. Modelling of SWCNT

To overcome the difficulty to dealing with the hollow cylinder of SWCNT, the solid cylinder model was adopted to represent the SWCNT. The transformation factor *TRF* between these structures was presented in previous works [9, 34]. In this work, the nano-solid tube material (NSTM) model is presented to model the SWCNT. The raw material of NSTM is derived from original material of SWCNT. This modelling approach aims to design and predict the EM properties of multi conductors CB-SWCNTs through design the CB-SWCNTs dipole antenna in the CST (MWS) software package. The conductivity of the NSTM model (σ_{NSTM}) is deduced from the surface conductivity of SWCNT (σ_{SWCNT}) presented in [9], as shown in the formula below:

$$\sigma_{NSTM} = \left(\frac{2}{r}\right)\sigma_{SWCNT} = -j\frac{4e^2 V_f}{\pi^2 h r^2 (w - jv)}\ . \qquad (19)$$

The plasma frequency (w_{psw}) of SWCNT can be estimated based on the bulk conductivity model presented in [9]. As well as, the relative complex permittivity of SWCNT (ε) is possible to estimate as shown below

$$w_{psw} = \frac{2e}{\pi r}\sqrt{\frac{V_f}{\varepsilon^o h}}\ , \qquad (20)$$

$$\varepsilon^{'} = 1 - \frac{w_{psw}^2}{w^2 + v^2}\ , \qquad (21)$$

$$\varepsilon^{"} = \frac{v\ w_{psw}^2}{w^3 + wv^2}\ . \qquad (22)$$

Where ($\varepsilon^{'}$) the real part and ($\varepsilon^{"}$) the imaginary part of the SWCNT relative complex permittivity. Hence, in order to implement the simulation technique of this modelling approach, the material parameters of the SWCNT are inserted in the CST (MWS) as a new normal.

III. APPLICATION OF CB-SWCNTS AND ESCM MODEL

In order to estimate the EM properties of CB-SWCNTs, the dipole antenna of both multi conductors CB-SWCNTs and corresponding ESCM model were applied and solved through CST (MWS). Furthermore, provide a comparison between these structures, in order to validate the ESCM model. The schematics of the CB-SWCNTs and ESCM dipole antennas are shown in Fig. 3.

With regard to both CB-SWCNTs and ESCM dipole antennas, in the CST (MWS) environment, the SWCNT material and CB-SWCNTs material were set up as new, normal materials in Drude method. Their parameters were inserted in the CST (MWS) to represent the equivalent NSTM model for SWCNTs and ESCM model to CB-SWCNTs. These parameters were previously extracted in this work. This process represents the modelling approaches for both SWCNT and CB-SWCNTs in the CST (MWS) software package in order to preface the design of different types of CNT antennas in the simulation mode. That means, a raw material of the equivalent NSTM model and ESCM model is derived from SWCNTs and CB-SWCNTs materials instead of deriving from other material.

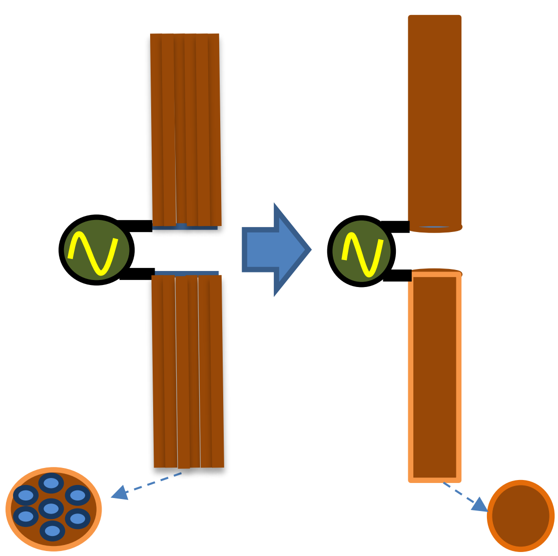

Fig. 3. Dipole antenna structure for both: (a) CB-SWCNTs and (b) ESCM model.

IV. MATCHING IMPEDANCE OF CB-SWCNT DIPOLE ANTENNA

In order to implement the CB-SWCNTs dipole antenna, the matching input impedance issue is demonstrated in this paper. Mathematically, based on the antenna concepts, the surface impedance is considered as an input impedance for dipole antenna [35]. Hence, according to the equivalent circuit diagram of the SWCNT presented by Burk [1-4], the input impedance of SWCNT antenna, which is equal to the input impedance of the equivalent nanowire model of SWCNT ($Z_{in,equvl}$) which presented in previous work [34], can be estimated. For simplicity, with regards to the SWCNT, the quantum parameters are given below:

$$Z_{in,equvl} = \frac{L}{\pi\sigma_{equvl} r^2} = \frac{L}{2\pi r\sigma_{SWCNT}}, \tag{23}$$

$$Z_{in,equvl} = Rq + jw\zeta. \tag{24}$$

Here, Rq is the quantum resistance, and ζ is the quantum inductance. These quantities are mathematically presented as follows:

$$Z_{in,equvl} = \frac{\pi hvL}{4e^2V_f} + jw\frac{\pi hL}{4e^2V_f}, \tag{25}$$

$$Rq = \frac{\pi hvL}{4e^2V_f} = \frac{3\pi hLT}{2re^2V_f}, \tag{26}$$

$$\zeta = \frac{\pi hL}{4e^2V_f}. \tag{27}$$

On the other hand, with regards to the CB-SWCNTs dipole antenna, the quantum resistance and quantum inductance can be estimated based on the general formula of the effective impedance of the bundle (Z_{bundle}) according to the impedance of SWCNT:

$$Z_{bundle} = \frac{Z_{in,equvl}}{N}. \tag{28}$$

For simplicity, the effective impedance of CB-SWCNTs based on the assumption that all SWCNTs are metallic, identical and arranged in the parallel structure. Thus, the quantum parameters of CB-SWCNTs are computed as given below:

$$R_{qB} = \frac{\pi hvL}{4Ne^2V_f} = \frac{3\pi hLT}{2Nre^2V_f}, \tag{29}$$

$$\zeta_B = \frac{\pi hL}{4Ne^2V_f}. \tag{30}$$

The one of the main problems of CB-SWCNTs dipole antenna is the matching issue between this antenna and the feeding source (discreet port). In this work, the simple matching approach is presented to mitigate this problem in simulation mode. This matching approach depends on adaptation the Normalized Fixed Impedance (NFI) value, which is one parameter of the s11 parameters setting window, in order to balancing the effectiveness of the input impedance of this dipole antenna with the internal impedance of the feeding source. The NFI option of the s11 parameters in CST (MWS) software package is very important when the initial value of the NFI is selected based on computing the value of R_{qB} from Equation (29). This value represents the impedance value that the system is needed to realize the matching between feeding source and dipole antenna (load). In another context, this value represents a starting value to obtain a well value of matching impedance between source and CB-SWCNTs dipole antenna to obtain the optimum result of s11 parameters. Indeed, the simple matching approach presented in this work is implemented for design CB-SWCNTs dipole antenna. As well as, this matching process is benefits for achieving the matching situation for different nanoelectronic antennas.

V. SIMULATION RESULTS AND DISCUSSION

In this work, the CST (MWS) software package is utilized to implement both equivalent modelling approaches, namely the NSTM for the SWCNT material to design multi conductors CB-SWCNTs, as well as ESCM to design single conductor which is corresponding to CB-SWCNTs, in which the dipole antenna configuration was employed to achieve this purpose. To design CB-SWCNTs dipole antenna, each packed of SWCNTs bundle will be connected to a square contact to make a feeding source touch all SWCNTs. The dimensions of this contact (length × width) are equal to ($W_D \times t$) and thickness is equal to (r). The discreet port was used as a feeding source for all dipole antennas designed in this work. The simulation results of this work could be implemented as follows.

A. Simulation results of CB-SWCNTs and ESCM model

In this section, both structures of CB-SWCNTs and ESCM modelling approach are implemented, in order to investigate the important material parameters of the CB-SWCNTs and to validate the ESCM modelling approach, based on comparison of their results. In addition, estimate the EM properties of CB-SWCNTs in different cross-section area (small and large cross section area) which contains different numbers of SWCNTs.

1. Investigation of CB-SWCNTs material parameters

In order to estimate and study the performance of the conductivity of the CB-SWCNTs (σ_{bundle}), which represent the conductivity of the equivalent ESCM model, the CB-SWCNTs included various numbers of the identical SWCNTs (N = 7, 19, 36, and 61) were implemented for this purpose. Figure 4 represent the behavior of the conductivity versus frequency, based on increases the number of SWCNTs in the bundle. Also, the plasma frequency of the bundle (w_{PB}) is affected by increases the number of SWCNTs (N) in the bundle, as shown in Fig. 5.

As a presented in these figures, the behavior of the conductivity of CB-SWCNTs was illustrated with increases the number of SWCNTs in this bundle (N). This mean, with increases the equivalent radius of the bundle. The plasma frequency of this bundle was decreased due to increases the radius of SWCNT. In contrary, the plasma frequency was increased due to increases the number of SWCNTs included in this bundle.

2. Validation of ESCM model

To validate the ESCM modelling approach, the dipole antenna configuration was designed based on the multi conductors CB-SWCNTs structure and the ESCM model. The CB-SWCNTs with different number of SWCNTs (N = 7, 19, 36 and 61) are mainly used with those corresponding cross-sectional area of ESCM model, in order to investigate the comparison between these structures. In addition, these two structures have the same lengths for designing the dipole antenna. All of the SWCNTs included in the bundle are identical, have the same radius (r = 2.71 nm). Similarly, the lattice distance (Δ) between the two adjacent SWCNTs is equally and equal to (0.34 nm). The length of dipole antenna is (L = 30 μm). The details of CB-SWCNTs and ESCM model are described in Table 1, in order to design the dipole antennas associated with these structures. The two types of dipole antennas centered by a feeding gap ($d = 2R_B$). The results of these antennas are shown in Fig. 6 for CB-SWCNTs and corresponding ESCM dipole antennas.

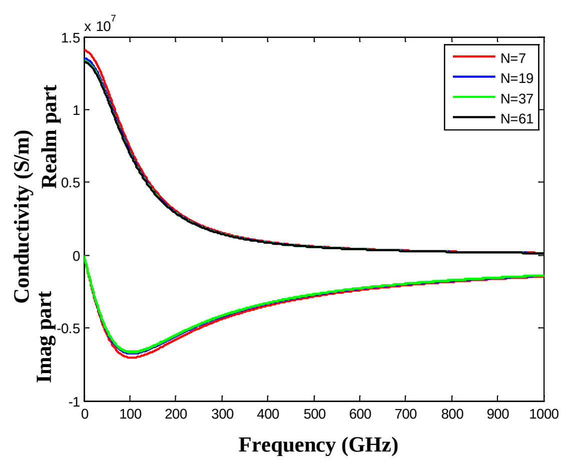

Fig. 4. The conductivity of B-SWCNTs (σ_{bundle}) versus the frequency with various number of SWCNTs (N).

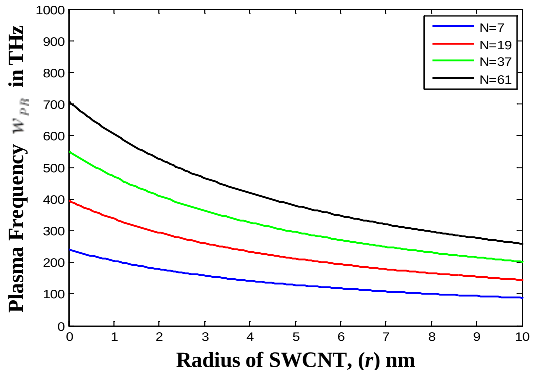

Fig. 5. Plasma frequency of CB-SWCNTs (w_{PB}) versus the radius of SWCNT with various number of SWCNTs (N).

Table 1: Details of B-SWCNTs and corresponding ESCM structures

Number of SWCNTs in the Outer Side of the Bundle Structure N_x	Total Number of SWCNT-s in the Bundle N	Corresponding Radius of CB-SWCNT-s and ESCM R_B (nm)	Cross-Section Area of CB-SWCNTs and ESCM A_B (Micrometer^2)
2	7	8.47	0.2254
3	19	14.23	0.6362
4	37	19.99	1.2554
5	61	25.75	2.0831

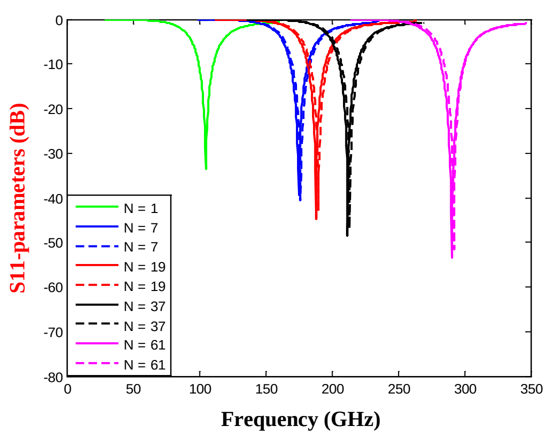

Fig. 6. Simulation results of multi conductor CB-SWCNTs at N = (7, 19, 37 and 61) and an equivalent ESCM dipole antennas. The solid lines are the CB-SWCNT results and the dotted lines are the ESCM results.

The simulation results of CB-SWCNTs and corresponding ESCM dipole antennas exhibited in Fig. 8, indicate the good conformity between the multi conductors CB-SWCNTs structure and ESCM model. As a result, by increasing the number of SWCNTs included in the bundle, the resonant frequency increases and the s11 parameters improved. Meanwhile, by increasing the cross-sectional area of the ESCM model, the same behavior was shown with related to resonant frequency and s11 parameters. In another context, the two structures, multi conductors CB-SWCNTs and ESCM model have the same response to changing the corresponding design parameters. These simulation results represent the EM behavior of CB-SWCNTs with a small cross-sectional area.

3. Verify the accuracy of modelling results

In order to verify the accuracy of the simulation results in this work, the comparisons between the results of CB-SWCNTs and ESCM modelling approach have been presented. The comparison between these structures was carried out based on the behaviour of the resonant frequency versus different number of the SWCNTs included in the bundle. Where, both dipole antennas have same length (L = 30 μm) and same cross-sectional area, which are changed based on the number of SWCNTs in the bundle. The comparison of these simulation results for both dipole antennas was illustrated in Fig. 7. Likewise, the other comparison for both dipole antennas has been implemented based on the efficiency of them, at the same length (L = 30 μm) and same cross-sectional area where (N = 7).

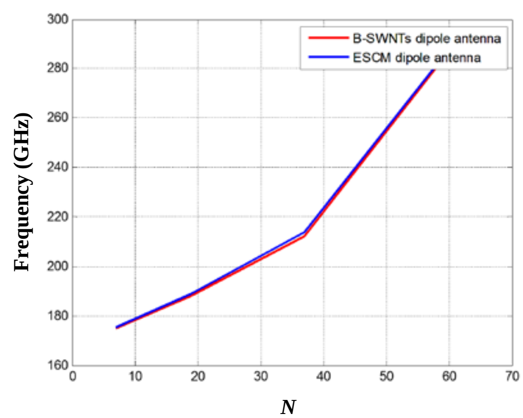

Fig. 7. Comparison results between CB-SWCNT and ESCM dipole antennas, based on the resonant frequency versus the number of SWCNTs included in the bundle at N = (7, 19, 37 and 61).

From the comparisons results presented in Fig. 7 and Fig. 8, a well accuracy results and compatibility can be observed between both CB-SWCNTs and ESCM dipole antennas. That means, the ESCM modelling approach has a good validation to represent the CB-SWCNTs material structure.

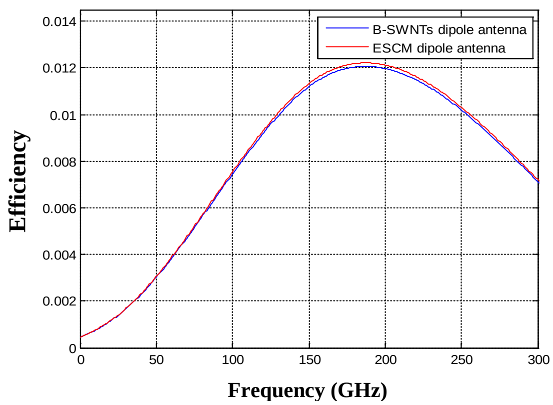

Fig. 8. Comparison results between CB-SWCNT and ESCM dipole antennas, based on the efficiency versus frequency at N = (7).

4. Electromagnetic behaviour of CB-SWCNTs with large cross-section area

The equivalent ESCM model for the CB-SWCNTs area was utilized to predict the electromagnetic properties of CB-SWCNTs with a large cross-section area, based on designing and implementing the ESCM dipole antenna into CST (MWS). The details of different cross-sectional areas of the CB-SWCNTs and corresponding ESCM model are described in Table 2, the cross-sectional areas were selected based on the number of SWCNTs (N) included in the bundle, which is related to the corresponding number of outer SWCNTs of hexagon for the original structure of CB-SWCNTs (N_x = 10, 20 and 30). With regard to these details, the dipole antennas are designed and implemented in CST (MWS), in order to investigate the EM properties of CB-SWCNTs at large scales geometric structures. The results of these antennas were shown in Fig. 9.

Table 2: Simulation details of ESCM that are equivalent to CB-SWCNTs structures

Number of SWCNTs in the Outer Side of the Bundle N_x	Radius of Equivalent ESCM Model to the CB-SWCNTs R_B (*Nanometre*)	Cross-Section Area of ESCM A_B (*Micrometer*^{2})	Corresponding Number of SWCNTs in the CB-SWCNTs N (*Tube*)
10	54.55	9.3484	271
20	112.15	39.5138	1141
30	169.75	90.5252	2611

From this result, the resonant frequency of ESCM dipole antenna was increased by increasing the cross-sectional area of ESCM model. Likewise, the s11 parameters of these dipole antennas improved. This result represents the starting phase to deal with a large geometrical structure of the CB-SWCNTs for the first time.

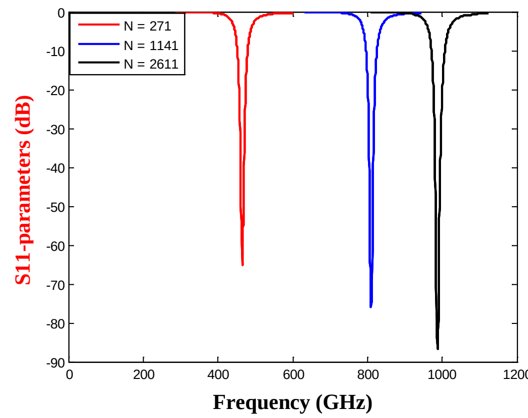

Fig. 9. Simulation results of ESCM dipole antenna with large cross-section areas, which are equivalent to N = (271, 1141, and 2611).

VI. CONCLUSION

In this paper, the two modelling approaches for SWCNT and CB-SWCNTs were presented and carried out into CST (MWS). To validate the ESCM modelling approach, the several numbers of SWCNTs which constructs the bundle with specific cross-section areas were designed and their results are also compared with those of similar cross-section area of the corresponding ESCM model. From these comparisons, a consistency of results was found between ESCM model and CB-SWCNTs.

The simulation results of ESCM and CB-SWCNTs dipole antennas demonstrated using of ESCM model to represent the CB-SWCNTs instead of CB-SWCNTs with hollow or solid cylinder SWCNTs structure. This led to reduce the overall complexity and solving the simulation time problem for estimation of EM properties for CB-SWCNTs with large number of SWCNTs.

The main goal of the ESCM modelling approach is to make a computation analysis less complicated at the simulation mode. The designing of ESCM model with a small and large cross-sectional areas corresponded to CB-SWCNTs with different numbers of SWCNTs make the estimation of the EM properties of CB-SWCNTs with a short time be compared with the traditional method of multi conductors CB-SWCNTs.

Actually, the performance evaluation indicators of CB-SWCNTs dipole antenna are dependent on the diameter and length of CB-SWCNTs, as well as the number of SWCNTs included in this bundle. Further optimization can be done to achieve better radiation performance, based on these performance indicators.

The contribution of this paper is to provide and validate the equivalent single conductor material (ESCM) model approach for the CB-SWCNTs using the CST (MWS) software package. The raw material of ESCM model is derived from the material properties of CB-SWCNTs.

Moreover, with regards to the antenna applications, the presented modelling approach for CB-SWCNTs is very useful and make possible to design antenna uses in on-chip wireless communication. This leads to make the CNTs is a candidate promising material for this purpose.

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Yaseen Naser Jurn was born in Baghdad, Iraq. He received the B.Sc. degree in Communication Engineering from the University of Technology, Baghdad, Iraq, in 1995, the M.Sc. degree in Communication Engineering (Direction of Arrival) from the Universiti Technology, Baghdad in 2002 and the Ph.D. degree in Communication Engineering (Nano Antenna Design) from the University Malaysia Perlis (UniMap), Perlis, Malaysia, in 2017. Currently he is a Senior Engineer in Minister of Science and Technology, Baghdad, Iraq, where he has been an Engineer since 1995 in Ministry of Science and Technology. His main personal research interests are modelling, simulation, and antenna design, antennas and propagations, electromagnetics, modern nanomaterial structure design, nano antenna design, modelling and simulation of nano antenna.

Mohamedfareq Abdulmalek obtained his B.Eng. (Hons.) - Electronic and Communication Engineering from the University of Birmingham, U. K. in 1997. He received his M.Sc. (Eng.) in Microelectronic Systems and Telecommunications at The University of Liverpool, U. K. in 2004 and Ph.D. Electrical Engineering (Radio Frequency and Microwave) in 2008 from The University of Liverpool, U. K. Recently, he is an Associate Professor in Faculty of Engineering and Information Sciences, University of Wollongong in Dubai. His main research interests are antenna design, embedded computing, microwave absorbers from agricultural waste and effects of RF on human's health.

Hasliza Binti A. Rahim received the Bachelor degree in Electrical Engineering from University of Southern California (USC), Los Angeles, USA in 2003. Later, she received the Master in Electronics Design System from the University Sains Malaysia, Transkrian, Pulau Pinang, Malaysia in 2006 and Ph.D in Communication Engineering from the University Malaysia Perlis, Perlis, Malaysia in 2015. She joined the School of Computer and Communication Engineering, UniMAP in 16th August 2006 as Lecturer and now as Senior Lecturer. She is the Head and Principle Researcher of Bioelectromagnetic Excellence Research Group (BioEM). Her extensive research area covers a range of applied engineering including advanced technologies for 4G/5G, antennas, wireless body area networks (WBAN), effects of RF on health, electromagnetics, and bioelectromagnetics. Several research funds were granted nationally such as Fundamental Research Grant Scheme, National ScienceFund, and Malaysian Communications and Multimedia Commission. She has authored and co-authored more than 50 peer reviewed scientific publications, including 2 articles in Nature Publishing Group journal (Scientific Reports), 3 patents, and 2 book chapters. She has been awarded with the Excellence

Woman Inventor by the University Malaysia Perlis in 2010.

Sawsen Abdulahadi Mahmood was born in Baghdad, Iraq. She obtained her B.Sc. in Mathematics from the University of Baghdad, Baghdad, Iraq, in 1992, the M.Sc. degree in Computer Science from the University of Technology, Baghdad, Iraq, in 2002. She received her Ph.D. in Computer Science at the Faculty of Computer Science in 2015 at University of Technology, Baghdad, Iraq. Recently, she is an Associate Professor in Faculty of Computer Science, University of Mustansiriyah, in Baghdad, Iraq. Her main personal research interests are Pattern Recognition and Machine Learning, 3D image analysis recognition, 3D video analysis, Surveillance System based on Internet of things environment, and Voice Recognition.

Liu Wei Wen obtained the B.Sc. with Education (B.Sc. Hons.) in Physics, 2002, from Physics Department, Faculty of Science, University Putra Malaysia (UPM), Serdang, Selangor. The M.Sc. in Materials Science, 2005 Physics Department, Faculty of Science, University Putra Malaysia (UPM), Serdang, Selangor. He received the Ph.D. in Nano Materials, 2012, from School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia (USM), Nibong Tebal, Penang. His main personal research interest is in synthesis of carbon nanotubes and graphene and their application in biosensor.