ABSTRACT We investigate the gate-controlled, electrically doped tunnelling current in Adenine-Thymine heterojunction nanotube-based Field Effect Transistor (FET). This analytical model FET is designed by Density Functional Theory (DFT) and Non-Equilibrium Green’s Function (NEGF) based First principle formalisms. It is demonstrated that Band to Band Tunnelling (BTBT) is possible in relaxed Adenine-Thymine heterostructure nanotube. The evaluation of BTBT tunnelling probability to estimate tunnelling current for only ±0.01V applied bias voltage is calculated using Wentzel-Kramers-Brillouin approximation. Electrical doping is introduced to eliminate the probability of fault generation. By keen observation on the shift of energy levels in the band structure, the availability of high transmission coefficient peaks and current-voltage response we demonstrate the Schottky barrier nature for this geometrically pre-optimized bio-molecular FET. The doping concentration is varied from 0.0001V to 0.1V to achieve a substantially large amount of tunnelling current when the electronic temperature is kept at 300K. The E-k diagram or complex band structure of this heterostructure nanotube ensures its in-direct semi-conducting nature. This is a first attempt to present a circuit-level demonstration using this Adenine-Thymine nanotube-based bio-molecular FET and validate the obtained results with the existing approaches.

INDEX TERMS Adenine-thymine, DFT, nanotube, NEGF, TFET.

I. INTRODUCTION

The tunnel FET (TFET) has been proved as a strong candidate for future generation low power application due to its low sub-threshold slope. Though Silicon does not achieve low sub-threshold slope and sufficiently high “ON”-state current due to its indirect energy bandgap, therefore alternative channel materials for FET are being investigated [1], [2]. In the field of organic electronics, recently Carbon Nano Tube (CNT), Graphene nano-ribbon based FETs draw the attraction of the researchers [1], [3]–[5]. Due to high carrier mobility and zero-band gap, graphene nano-ribbon FET fails to prove itself in the field of transistor application [1], [6]. Researchers are also trying to find an alternative TFET due to the presence of leakage current in the MOSFET which uses SiO$_2$ as gate dielectric [7], [8].

In this study, BTBT probability through the bio-molecular channel has been investigated using DFT conjugated with NEGF based First principle approach with the help of Atomistix Tool Kit-Virtual Nano Laboratory (ATK-VNL) software simulator package version 12.8.0. Considering Poisson’s solution the drain current of this bio-molecular TFET is being investigated at 300K electronic temperature. To avoid the probability of fault arising, electrical doping is introduced to design the analytical model TFET. In case of electrical doping, a potential drop is to be created between the two terminals of a system or in this case the two terminals of electrodes by inducing two different and opposite potentials
at the two ends of the electrodes. The difference between the two potentials leads to movement of charge from one terminal to another through the central molecular region. Even more, the amount of electrical doping can be calculated using the length, width, height and the amount of charge which is applied at the two terminals of the molecular device. On the contrary, normal doping is the process to incorporate dopants (either n-type or p-type impurity) into the materials by ionization technique or by ion bombarding method. This process is a high-temperature process. This process leads to some fault generation within the materials as it is a high heat process.

The comparison Table 1 show a comparative study between the existing FET’s and the proposed Adenine-Thymine nanotube-based TFET.

The major contributions of this work are listed as follows:
1. An approach to design an analytical model of Adenine-Thymine based heterojunction bio-molecular nanotube-based TFET.
2. Sufficiently large current obtained and the Current-Voltage (I-V) response follows almost the same characteristics of conventional FET.
3. This is an approach to analytically design molecular level circuit (mainly logic devices) and validate the result with the result obtained from the multi-sim software simulator.

II. COMPUTATIONAL METHOD
The quantum-ballistic BTBT is observed for the theoretical model of Adenine-Thymine based nanotube TFET. This bio-molecular TFET is designed using $1 \times 1 \times 100$ K-point samplings and 75 Hartree mesh cut-off energy.

The molecular device has extremely small dimensions for width (X-direction) and height (Y-direction) compared to its’ length. The length is considered to be projected along Z-direction. To minimize error-free calculation, the number of K-point sampling has been increased along the length or Z-direction. Increasing the no. of samples along Z-direction, we increase the no. of samples along the central scattering region of the molecules and therefore, the more accurate and significant result has been obtained. Density Functional Theory (DFT) calculations and LDA-GGA functional are used in this manuscript. DFT reduces the quantum mechanical ground state many-electron problem to self-consistent one-electron form, through the Kohn-Sham equations. To calculate the quantum-mechanical transport phenomenon DFT is used in this calculation. This technique is also a good balance between computational cost and accuracy. This method also describes the exchange-correlation functional of the molecules. Moreover, DFT is, in principle, more accurate explicitly correlated quantum chemistry method to describe the function of the molecular devices.

LDA-GGA method is the local density approximation-generalized gradient approximation method. This method provides a possible explanation for the predicted low diffusion coefficients for the simulations of the molecular device and raises a general concern over the ability of pure functional to describe the intra-molecular deformation and also highlighting the importance of exact exchange in simulations.
of at molecular level. More specifically LDA shows in terms of the electron density at that point. This also means that the exchange-correlation functional which was recorded as an integral of a certain function of spatial variables of the central molecular region of the device.

DFT process is officially exact, but for realistic calculations, the exchange-correlation energy as a functional of the density must be approximated. For this reason, LDA is a standard choice. Simple LDA results in a realistic description of the atomic structure, elastic, and vibration properties for broad varieties of systems. Yet, LDA is generally not so accurate to describe the energy of chemical reactions (for example, heats of reaction and activation energy barriers), leading to an over the rate of the binding energies of molecules and solids in particular. Recently, GGA’s have overcome such deficiencies to a considerable extent, giving, for instance, a more realistic description of energy barriers in the dissociative adsorption of hydrogen on metal and semiconductor surfaces. Gradient corrected or GGA functions depend on the local density as well as on the spatial variation of the density.

The maximum tolerance parameter is $10^{-5}$ along with 200 steps of operation. The simulation parameters are required for this theoretical modelling of nano FET, shown in Table 2.

The working principle and work-flow model of Quantum-wise software are illustrated in Fig.1.

III. RESULTS AND DISCUSSION
This work presents an analytical approach to design Adenine and Thymine bio-molecule based heterojunction nanotube TFET using First principle formalisms. Therefore, at first, we take two $4 \times 4$ nanolayers of Adenine and Thymine bio-molecules. After the necessary simulation arrangements, this heterostructure nanotube has been analytically designed. Henceforth, the nanotube is aligned properly and also geometrically optimized to reduce the stress at a molecular level. The nanotube is 2.44nm long and 0.83nm wide. This molecular device is divided into three main portions, viz; left electrode (LE), right electrode (RE) and central molecular region, which are mentioned in Fig. 2. Additional metallic gate with a small di-electric layer is placed at the top of this bio-molecular nanotube to form the TFET. The LE and RE are 0.5nm long. This two probe experiment is carried out using ATK-VNL software simulator package of version 12.8.0.
This atomistix bio-molecular TFET shows almost ideal characteristics like conventional FET. Adenine and Thymine are two crucial molecules of the human body which form the DNA chain. Adenine converts itself into adenosine-tri-phosphate (ATP) and takes an active part in human metabolism. Adenine and Thymine chain based electrically doped p-i-n FET is already reported [11]. The various quantum-electronic characteristics of this bio-molecular nanotube-based TFET have been observed such as:

1. Transmission spectra.
2. Device Density of States.
3. I-V characteristics.
4. Conductance
5. Circuit level implementation and its validation.

This nanoscale bio-molecular TFET is designed considering electrical doping procedure to form p and n regions at the two ends of the nanotube. The structural information of the bio-molecular TFET is observed in Table 3.

The procedure of electron contribution and electron acceptation to the molecular thin films is described as electrical doping. Introducing this procedure molecular interface can be modified [11]–[13]. There are several advantages of electrical doping, some of them are increased device efficiency when injecting carrier at the molecular interfaces and molecular film conductivity increased to a great extent, Ohmic contact can be achieved on inorganic semiconductor without using conventional dopants etc. [11], [14], [15]. The doping concentration is calculated using the following calculation in Eq. (1)

\[
\text{Effective doping concentration} = \text{doping/volume} \ [11], \ [16]
\]

In this work, the electrical doping charge is varied from ±0.001V to ±0.1V. Assume Effective doping charge= ±0.1V.

### Table 3. Structural information of p and n bio-molecular TFET.

| Bio-nanotube TFET structural specification | n-type bio TFET | p-type bio TFET |
|------------------------------------------|----------------|----------------|
| Channel length                           | 2.45 nm        | 2.45 nm        |
| Gate length                              | 1 mm           | 1 mm           |
| Nanotube diameter                        | 3.84 nm        | 3.84 nm        |
| Nanotube length                          | 1.72 nm        | 1.72 nm        |
| Source doping                            | 5.45×10^18    | 5.45×10^18    |
| Drain doping                             | 5.45×10^18    | 5.45×10^18    |
| Gate di-electric thickness               | 0.1 nm         | 0.1 nm         |
| Aspect ratio                             | 2.2            | 2.2            |
| Conductance gm                           | 4.62×10^4 S    | 3.39×10^3 S    |
| Drain resistance \( I_d \)              | 4.9×10^6Ω      | 1.53×10^2Ω     |
| Amplification factor \( \mu \)          | 2.27           | 5.17           |

### Table 4. Doping concentration w.r.t. Applied electrical charge.

| Electrical Charge (V) | Doping concentration (per cc) |
|-----------------------|------------------------------|
| ±0.001                | 5.45×10^17                  |
| ±0.01                 | 5.45×10^18                  |
| ±0.1                  | 5.45×10^19                  |

Volume of the nanotube=\( \text{length} \times \text{width} \times \text{height} = (2.44×10^{-7}) \times (0.83 \times 10^{-7}) \times (0.9 \times 10^{-7}) \text{cm}^{-3} = 1.822 \times 10^{-21} \)

\[
\text{Hence, Effective doping} = \frac{0.1}{1.822 \times 10^{-21}} = 5.45 \times 10^{19}/\text{cm}^3 \quad (1)
\]

Doping concentrations obtained for various potentials are listed in Table 4.

### A. Transmission Spectra

Transmission spectra are the amount of electromagnetic radiation which can pass through inter atomic passage. The sharp and wide peak of transmission assures the availability of the channels within the central molecular region.

It is also observed that, if the number of available peaks is increased within the bias window that means large numbers of channels are available. Therefore, the high tunnelling current can flow through the central molecular region. Bias window simply depends on the amount of electrical doping charge. If the doping concentration is high then the transmission is also high. The compared transmission spectra are shown in Fig. 3, where ‘green’ colour represents transmission spectra when doping charge is ±0.001V and ‘red’ line shows transmission spectra for ±0.01V doping charge. Hence transmission co-efficient simply depends on the applied bias and the energy levels, that can be formulated using Green’s function in Eq. (2)

\[
T(E, V_d) = T_r \left( \Gamma_l G_r \Gamma_r G_l \right)
\]
FIGURE 3. Compared transmission spectra of bio-molecular nanotube TFET.

where bias dependent transmission co-efficient is expressed as $T(E, V_d)$, the impeded and complex Green’s function of the fundamental bio-molecular scattering segment is articulated as $G^{R/A}$ [17]. Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO) for the two doping conditions are shown in Fig. 3. HOMO and LUMO are referred to as the maxima of the valence band and the minima of the conduction band respectively. The difference between HOMO and LUMO signifies the thermodynamic stability of the molecule. It is also signified that if the gap between these two is maximum then the potential barrier is high which results in less amount of carrier transmission. Minimum gap between HOMO and LUMO means small potential barrier thus it contributes towards high carrier transmission.

B. I-V CHARACTERISTICS

The Current-Voltage (I-V) response of this hetero-structure nanotube supported Adenine-Thymine TFET is shown in Fig. 4 (a). The I-V characteristics which are revealed in Fig. 4 (a), is the result of quantum-ballistic transmission carrier within the central molecular region. This characteristic depends on the electrical doping concentration. When the doping concentration increases then the amount of current transmission also increases. From Fig. 4(a) it is evident that large current is obtained for n-channel whereas very less amount of current has been observed for p-channel.

The contact potential at p and n region has been dropped due to electrical doping. The electrons near the orbital of the Fermi level ($E_F$) are de-localized and also accountable for this current transportation phenomenon within the central molecular region. If conduction band ($E_c$) is very close to the $E_F$ than valence band ($E_v$) then the main donors are received from LUMO. At enough bias voltage $E_c$ shifts in the direction of $E_F$, and thus energy gap moves near lesser energy height. Therefore, at this bias additional conducting channels contributes to the carrier transportation [18]. This bias voltage is known as the threshold voltage of this TFET. The quantum-ballistic current is formulated in Eq. (3) [11].

$$I_d = \frac{2e^2}{h} \int_{-\alpha}^{+\alpha} T(E, V_d) \left[ f_L(E-\mu_L) - f_R(E-\mu_R) \right]$$ \hspace{1cm} (3)

In Eq. (3), $I_d$ is dependent on $T(E, V_d)$ which is bias dependent (here doping charge-dependent) transmission co-efficient, $f_L/R$ is the Fermi levels for left and right electrodes, $\mu_{L/R}$ is the chemical potentials of the left and right electrodes. It is observed from Eq. (3), that the drain current $I_d$ is dependent on transmission co-efficient. As a result, for the availability of high transmission peaks which are responsible for higher current is obtained. Above threshold bias voltage more transmission peaks are available due to the availability of more energy states. Therefore, a higher current is obtained above threshold voltage [19], [20].

The drain current ($I_d$) vs Source to drain bias ($V_{ds}$) for different gate bias is shown in Fig. 4(a). The $I_d-V_g$ graph for this TFET is also shown in Fig. 5 (a). These two graphs show that this bio-molecular TFET shows almost the same I-V characteristics like conventional FET.

The compared I-V characteristics for this device at circuit level modelling and for atomistic simulation, when the gate bias is constant, which is shown in Fig. 4 (b).
FIGURE 5. (a) $I_d$–$V_g$ graph of bio-molecular nanotube TFET. (b) Multi-sim simulated I-V graph of the circuit model representation for FET (solid line) and the atomistic simulated data (plus symbols) of the same device when $V_{ds}$ is constant.

C. CONDUCTANCE

The quantum-ballistic transmission property of the device determines channel conductivity of this bio-molecular TFET. This is another important parameter which determines device performance. Channel conductivity depends on the available number of channels present within the transmission bias window.

If this number is higher that means due to the availability of large numbers of channels device conductivity is high. These available channels are responsible for carrier transmission. It is evident from Eq. (3), that $I_d$ is dependent onto the channel’s transmission co-efficient. Hence, for the presence of a large number of channels within the bias window increase the channel conductivity [20].

Increasing values of electrical doping concentration increase carrier transmission probability, which is responsible for the high conductivity of the molecular channel. This electrical doping is actually the functional bias at the two terminals of the electrodes, which is also indicated as a source to drain bias $V_{ds}$. This applied bias is responsible to introduce a potential drop which proceeds as strong potential for introducing conductivity within the channel. When doping density grows, it amplifies the bias; therefore channel conductivity is getting enhanced. The thermal conductivity which is shown in Fig. 6 mainly occurs for electron transmission.

The conductivity of this molecular device is formulated using the Landauer Büttiker formula which is indicated in Eq. (4), where $G$ is the conductivity of the molecular channel, $T(E,V_{ds})$ is the bias dependent transmission co-efficient, $f$ is the average Fermi level.

$$G = \int_{-\infty}^{+\infty} dE T(E,V_{ds}) \left(-\frac{df}{dt}\right)$$

The differences in structural and electronic properties of these $p$ and $n$ FET are shown in Table 5. The surface potential $V_s$
D. CIRCUIT LEVEL IMPLEMENTATION AND ITS VALIDATION

It is obvious that adjacent atoms attract shared electrons which are present in a covalent bond with the highest electronegativity. It is a known fact in electromagnetism; positive electrostatic potential attracts negative charge and vice-versa. It is implied that an atom which achieves an affirmative electrostatic potential $V_p$ and the adjacent atom will not be influenced till $V_p$ exceed a given threshold bias $V_{th}$. When $V_p$ equal to or go beyond $V_{th}$, then only current flow through the tiny molecular channel. $V_p-V_{th}$ is actually the potential at which exactly no current is available. This $V_{th}$ value depends on the polarity of the bond. Gate bias plays an important role in case of activation of the molecular device. When an applied bias voltage is greater than $V_p-V_{th}$ then only current flows and the device gets activated. This $V_{th}$ depends on the applied potential bias at the gate during the nanoscale simulation process of this A-T based TFET.

The threshold voltage level is used to vary the concentration of electrical doping, which leads to moving the Fermi height of left and right electrodes. Electrical doping concentration is to be changed by changing the potential bias at the two electrodes. Fig. 8 (a)-(d) shows the output observed for the two universal gates NOR and NAND, using this TFET which is originated from Adenine-Thymine nanotube structure and then the results are validated with the graphs obtained from Multi-sim 11.1 [20].

As per the circuit level representation when the applied drain to source bias ($V_{ds}$) voltage exceeds the $V_p-V_{th}$ value, then current transmits in forward bias. In reverse bias, applied voltage ($V_{ds}$) is slightly more than $V_p-V_{th}$ and therefore almost no current transmits excluding insignificant leakage.
current. So the condition for current flows is shown in Eq. (5).

\[ V_{ds} \geq V_{th,l} + 2V_{th} \]  

(5)

In Eq. (5), \( V_{th,l} \) is the modified threshold voltage which has been set for connecting atoms. If \( V_{ds} \) is not same or even exceed \( V_{th,l} + 2V_{th} \), then movement of the current in reverse bias is not possible. The I-V response graph of the circuit level execution of the device and result obtained during the nanoscale simulation is shown in Fig. 5(a). Two universal logic gates NAND and NOR are satisfactorily implemented using atomistix simulation [19], [20].

The statistical comparative study of the various features of the proposed TFET along with the existing FET’s is illustrated in Table 6.

### IV. CONCLUSION

A detailed analytical model of Adenine-Thymine heterojunction nanotube-based TFET is represented and its’ quantum-ballistic transmission is investigated. The I-V response for various applied bias and (at various electrical doping) has been illustrated. Significantly, 61\( \mu \)A current is achieved at 2V applied bias during room-temperature operation. It has been observed that the conductivity of the channel increases due to electronic transmission and increasing electrical doping concentration. This simulated work is carried out at 1000 THz frequency. The I-V response of this TFET at different bias helps to implement NAND and NOR logic gates. The results are therefore validated with the existing approach. We expect that this bio-inspired TFET increase the possibility of the future generation circuit-level execution using molecular devices.

### REFERENCES

[1] R. K. Ghosh and S. Mahapatra, “Proposal for Graphene–Boron nitride heterobilayer-based tunnel FET,” *IEEE Trans. Nanotechnol.*, vol. 12, no. 5, pp. 665–667, Sep. 2013.

[2] A. Schenk, “Rigorous theory and simplified model of the band-to-band tunneling in silicon,” *Solid-State Electron.*, vol. 36, no. 1, pp. 19–34, Jan. 1993.

[3] L. Leem, A. Srivastava, S. Li, B. Maggari-Kope, G. Iannaccone, J. S. Harris, and G. Fiori, “Multi-scale simulation of partially unzipped CNT hetero-junction tunneling field effect transistor,” in *IEDM Tech. Dig.*, Dec. 2010, pp. 32.5.1–32.5.4. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5703465

[4] S. K. Gupta and G. N. Jaiswal, “Study of nitrogen terminated doped zigzag GNR FET exhibiting negative differential resistance,” *Superlattices Microstruct.*, vol. 86, pp. 355–362, Oct. 2015.

[5] K.-T. Lam and G. Liang, “Computational study on the performance comparison of monolayer and bilayer zigzag graphene nanoribbon FETs,” in *Proc. 13th Int. Workshop Comput. Electron.*, May 2009, pp. 1–4. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5091098

[6] Y. Zhang, T-T. Tang, C. Girit, Z. Hao, M. C. Martin, A. Zettl, M. F. Crommie, Y. R. Shen, and F. Wang, “Direct observation of a widely tunable bandgap in bilayer graphene,” *Nature*, vol. 459, no. 7248, pp. 820–823, Jun. 2009.

[7] E. Nadimi, R. Oettking, P. Pfäutzner, M. Schreiber, and C. Radehaus, “First-principles investigations of the leakage current through strained SiO\(_2\) gate dielectrics in MOSFETs,” in *Proc. IEEE Semiconduct. Conf. Dresden (SCD)*, Sep. 2011, pp. 1–4. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/6068768

[8] E. Nadimi, P. Pfäutzner, R. Oettking, K. Wieczorek, and C. Radehaus, “First principle calculation of the leakage current through Si\(_2\)O\(_3\) and Si\(_2\)O\(_3\)N\(_2\) gate dielectrics in MOSFETs,” *IEEE Trans. Electron Devices*, vol. 57, no. 3, pp. 690–695, Mar. 2010.

[9] L.-N. Zhao, X.-F. Wang, Z.-H. Yao, Z.-F. Hou, M. Yee, X. Zhou, S.-H. Lin, and T.-S. Lee, “Atmomic modeling of the electrostatic and transport properties of a simplified nanoscale field effect transistor,” *J. Comput. Electron.*, vol. 7, no. 4, pp. 500–508, Dec. 2008.

[10] M. Tabe, D. Moraru, E. Hamid, A. Samanta, L. T. Anh, T. Mizuno, and H. Mizuta, “(Invited) dopant-atom-based tunnel SOI–MOSFETs,” *ECS Trans.*, vol. 58, no. 9, pp. 89–95, Aug. 2013.

[11] D. Dey, D. De, and P. Roy, “Electronic characterisation of atomistic modelling based electrically doped nano bio p-i-n FET,” *IET Comput. Digit. Tech.*, vol. 10, no. 5, pp. 273–285, Sep. 2016.

[12] W. Gao and A. Kahn, “Electrical doping: The impact on interfaces of \( \pi \)-conjugated molecular films,” *J. Phys., Condens. Matter*, vol. 15, no. 38, pp. S2757–S2770, Oct. 2003.

[13] S. L. Rudaz, “Maximizing electrical doping while reducing material cracking in III-V nitride semiconductor devices,” U.S. Patent 5 729 029 A, Mar. 17 1998.

[14] A. Kahn, N. Koch, and W. Gao, “Electronic structure and electrical properties of interfaces between metals and \( \pi \)-conjugated molecular films,” *J. Polym. Sci. B, Polym. Phys.*, vol. 41, no. 21, pp. 2529–2548, Nov. 2003.

[15] S. Yu, J. Frisch, O. Opitek, E. Cohen, M. Bendikov, N. Koch, and I. Salzmann, “Effect of molecular electrical doping on polyfuran based photovoltaic cells,” *Appl. Phys. Lett.*, vol. 106, no. 20, May 2015, Art. no. 203301.

[16] (2013). Silicon Nanowires: Tutorial, Version 12.8. QuantumWise AS. Atomistix ToolKit (ATK), QuantumWise Simulator. [Online]. Available: http://www.quantumwise.com

[17] Y.-C. Ling, F. Ning, Y.-H. Zhou, and K.-Q. Chen, “Rectifying behavior and negative differential resistance in triangular graphene p–n junctions induced by vertex B–N mixture doping,” *Organic Electron.*, vol. 19, pp. 92–97, Apr. 2015.

[18] P. Bai, K. T. Lam, E. Li, and K. K.-F. Chang, “A comprehensive atomic study of carbon nanotube Schottky diode using first principles approach,” in *IEDM Tech. Dig.*, Dec. 2007, pp. 749–752. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/4419005

[19] A. Mahmoud and P. Lugli, “Towards circuit modeling of molecular devices,” *IEEE Trans. Nanotechnol.*, vol. 13, no. 3, pp. 510–516, May 2014.

[20] D. Dey and D. De, “A first principle approach toward circuit level modeling of electrically doped gated diode from single wall thymine nanotube-like structure,” *Microsyst. Technol.*, vol. 24, no. 7, pp. 3107–3121, Jul. 2018.

**DEBARATI DEY** received the master’s degree in technology (M.Tech. in VLSI design) from the University of Calcutta, in 2011. She worked in several organizations, such as Onida, Bengal College of Engineering and Technology. She is currently an Assistant Professor with the Department of Electronics Communication and Engineering, B. P. Poddar Institute of Management and Technology, Kolkata, She is the author of the book chapter published by NOVA, USA. Her research interests are in nano technology, quantum cellular automata, and bio-inspired computing.

**DEBASHIS DE** (Senior Member, IEEE) is currently a Professor with the Department of Computer Science and Engineering, Maulana Abul Kalam Azad University of Technology (formerly known as West Bengal University of Technology), Kolkata. He is also an Adjunct Research Fellow of The University of Western Australia, Perth, Australia. His research area includes location and power management in mobile network and mobile cloud computing. He received Young Scientist award both in 2005 at New Delhi and in 2011 at Istanbul by International Union of Radio Science, Belgium.
FERIAL GHAEMI received the Ph.D. degree in nanotechnology from the Institute for Advanced Technology, Universiti Putra Malaysia, in 2015. She joined the Institute for Tropical Forestry and Forest Products, in 2016, where she is currently a Postdoctoral Research Fellow. She published more than 30 research works in prestigious CIJ journals. Her main research interests are on synthesis of different types of nanomaterials with applications arising in drug delivery, polymer composites, and microextraction techniques.

ALI AHMADIAN received the Ph.D. degree in applied mathematics from the Universiti Putra Malaysia, Serdang, Selangor, Malaysia, in 2013. He is currently a Fellow Researcher with Universiti Putra Malaysia. He has published more than 60 peer-reviewed scientific publications. He is a Reviewer for 60 international journals. He was involved in several national and international projects related to the applications of fuzzy systems in the real-world systems. His current research interests include fuzzy fractional calculus, interval-valued functions and spectral methods for the solution of fuzzy differential equations, and fuzzy mathematical modeling.

LUQMAN CHUAH ABDULLAH received the Ph.D. degree in chemical engineering from the University of Birmingham, U.K., in 2000. He is currently with the Institute for Tropical Forestry and Forest Products, Universiti Putra Malaysia. As an active researcher, he has published more than 300 journals and other publications. His research interests are in the areas of chemical processing, environmental engineering, oleochemical, air pollution control, energy storage and phase change materials, and process modelling and simulation. He also has a strong research collaboration with various national and international research institutions. He received the Young Engineer Award from the Institution of Engineers Malaysia (IEM), the Top Research Scientist Malaysia (TRSM) by the Academic of Science Malaysia, in 2013, and the Malaysia Rising Star Award by the Ministry of Higher Education, Malaysia, in 2015.