Commercial and Open Source Electromagnetic Simulators for Education, Research and Industrial Design

Kok Yeow You*, Chia Wui Lee, and Chia Yew Lee
Department of Communication Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia
* kyyou@fke.utm.my

Abstract. In this paper, the development and importance of commercial and open source electromagnetic simulation software on education, research and industrial design, has been briefly reviewed. The EM simulators are increasingly being used by engineers and researchers in the RF device design, as well as the engineering curriculum. Thus, a study for open source EM simulator was conducted in the university. The study of simulator was created based on the FDTD techniques which are particularly used for solving RF monopole problems; MATLAB graphic user interface feature has been applied. The comparison result between the study simulator and commercial EM simulator are discussed and analyzed.

Keywords: Open source, commercial EM simulator, finite element method, method of moment, finite difference time-domain.

1. Introduction

With the advent of computer technology in 1960, attention to the usage of numerical Electromagnetic (EM) methods in communication devices design has raised increasingly. These methods include Finite Difference Method (FDM), Finite Difference Time-Domain (FDTD) [1], Moment Method (MoM) [2] and Finite Element Method (FEM) [3]. Subsequently, methods such as Uniform Theory of Diffraction (UTD/GTD) [4], Finite Integration Technique (FIT) [5], Transmission Line Matrix (TLM), Physical Optics (PO) and etc, were studied depending on the operating frequency and geometrical complexity, which had to be resolved. Starting in the 1980s, the numerical EM methods have been intensively studied in universities. Until the end of 1990s, a lot of EM simulator software from the results of the study have been commercialized. Recently, the EM simulator has an important role in the communication industry sector as well as research universities. Communication technology is increasingly pointing towards 5G where operating frequency has been changed from 2.4 GHz/5.8 GHz to 28 GHz and 38 GHz [6], as well as the RF communication devices; In future, these devices must be very small and sensitive. Thus, the invention work urgently needs assistance from EM simulator for their product design. For instance, with the EM simulator, new mobile phone model can be designed within a short time in order to meet the competition of the global market. In addition, the risks of trial-and-error in the experiment design can be diminished.

Besides, research activities in the field of communications, especially in wireless and sensor studies, have been carried out rapidly in universities around the world. Existing analytical theory in electromagnetic textbook is not adequate for use in the invention of the latest complex RF devices. Hence, analytical methods for designing RF devices have been replaced by numerical EM methods. In fact, numerical EM methods are combined knowledge of four major subfields as shown in Figure 1.

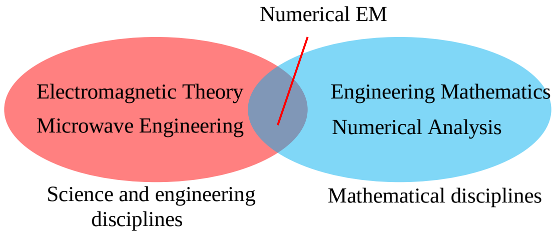


Fig.1. The definition of numerical EM.

Despite that the physics and electrical/electronic (EE) engineering students have to take electromagnetic theory and engineering mathematics courses, however, both courses apparently do not seem to relate to each other. Normally, physics or EE engineering students do not have problems in understanding the basic principles and advanced electromagnetic, nonetheless, they are less familiar with mathematical expressions and numerical methods, such as iterative method and numerical integration. On the other hand, majority of students from mathematic fields have less opportunity to explore the principles of electromagnetic and likewise its application. This situation has created an obstacle and a huge challenge in the development of numerical EM methods study at the university.

In recent years, learning outcomes for electrical engineering course in university has tended towards design and other professional skills. Out of these reasons, the numerical EM subject should be offered in the university. This course will help future scientist or engineer to become proficient in one of the commercial EM simulator since they have basic knowledge concerning the concept, definition, and parameters used in the software. Moreover, there is still a possibility to implement this study at the level of postgraduate. To learn numerical EM methods effectively, students/researchers and engineers should be acquainted with at least one of the programming language, such as Fortran or MATLAB. Normally, numerical methods involving matrix or iterative solutions, have more than thousands of unknown parameters to be solved. Therefore, it is less likely that numerical calculations could be done manually. On the commercial level, a complete EM simulator package includes automatic adaptive and graphical user interface (GUI) features, which requires an expertise of six sub-areas as labeled in Figure 2. In fact, a fast, stable, accurate and multifunction EM simulator needs a vast material, financial resource, manpower and time to complete it. Thus, development of the complete EM simulator requires funding support and a group of researchers/engineers from universities or private companies. Basically, a solver for most of the EM simulators involves a combination of several numerical methods (so-called hybrid technique), in order to solve various cases of EM problem. However, the main frame solver of those EM simulators is usually based on the three well-known methods: FEM, MoM and FDM/FDTD, respectively, as tabulated in Table 1.

Besides commercial software, many FEM-, MoM- and FDTD-based open source software have been released recently. For instance, open source FDTD-based EM software package, namely MEEP [7], openEMS [8] and gprMax [9] from Massachusetts Institute of Technology (MIT), Duissenberg University and Edinburgh University, respectively. Furthermore, the other examples of the FEM-, MoM- and UTD/GTD-based open source EM software are MaxFEM, FEMM, NEC, GLMoM, MMANA-GAL, EM3DS, newFASANT, EMCoS, WedgeGUI [10] etc. Normally, the EM problems that can be solved by the above-mentioned software are limited compared to the commercial one. In this paper, a simple and user-friendly FDTD-based 2D simulator written in MATLAB codes is developed for RF monopoles driven from coaxial line. As a matter of fact, applications for RF monopole is widely extended, which can be used as an antenna, *E*-field probe, sensors, hyperthermia radiator etc. The further detail of the studied simulator was described in Section 2.

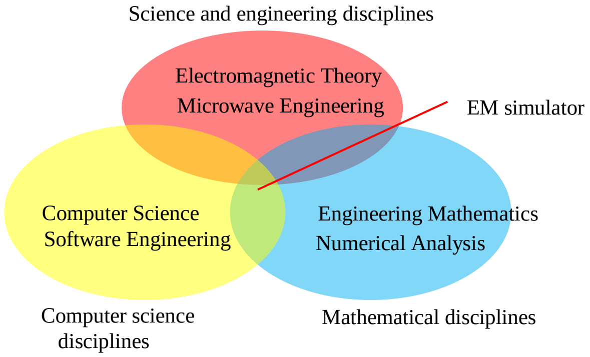


Fig.2. The definition of EM simulator.

Table 1: List of several commercial EM software.

Commercial Software	Main Solver
HFSS	FEM for arbitrary geometry
COMSOL RF Module	FEM for arbitrary geometry
MiniNEC Professional	MoM for thin wire structures
Sonnet Suites	MoM for planar structures
MWO	MoM for planar structures
FEKO	MoM for arbitrary geometry
XFDTD	FDTD for arbitrary geometry
QuickWave	Conformal FDTD

2. FDTD-based EM simulator

2.1. Design concept of the studied simulator

In this work, the FDTD in the simulator is focused on the 2D sub-cell model [11] for the monopole driven from coaxial line. To simplify the complexity of the computation, several assumptions are made as such:

(a) Electromagnetic wave propagation is modeled in 2D axially symmetrical cylindrical coordinates (x–y)
(b) The propagation wave in coaxial line is assumed only in transverse electromagnetic (TEM) mode.
(c) The scattering wave is characterized by transverse magnetic (TM) fields in external radiation region.
(d) All metal conductors in the simulation are defined as perfect electric conductor (PEC).
(e) The computational domain is truncated by convolution perfectly matched layer (CPML).
(f) The dielectric property of the external medium region is assumed to be homogeneous and isotropic.
(g) The thermal analysis will only consider the external medium region and exclude the monopole region.

The simulation domain is truncated using convolution perfectly matched layer (CPML) in order to absorb all outgoing electromagnetic waves [12]. To minimize the reflection, $\Gamma \approx 0$ at PML, conductivity, $\sigma(x)$ within the PML is graded smoothly along the PML from zero to maximum at the front of PML interface as shown in Figure 3. The polynomial grading of conductivity, $\sigma(x)$ is given as [11]:

$$\sigma(x_n) = \sigma_{\max}\left(\frac{x_n}{d}\right)^m \qquad (1)$$

where x_n is the thickness for n^{th} layer within the PML. Symbol d is the total thickness of the PML, m is the degree of polynomial. The theoretical reflection factor, $\Gamma(\theta)$ of the simulation, which is related to the conductivity, σ of the PML in (1) was predicted as [12]:

$$\Gamma(\theta) = \exp\left\{-2\varepsilon_o\sigma_{\max} d\cos\theta \Big/ \left[c\left(m+1\right)\right]\right\} \qquad (2)$$

where θ is the normal angle of the incident wave on the PML boundary. Symbols ε_o and c are the permittivity and the speech of light in vacuum, respectively.

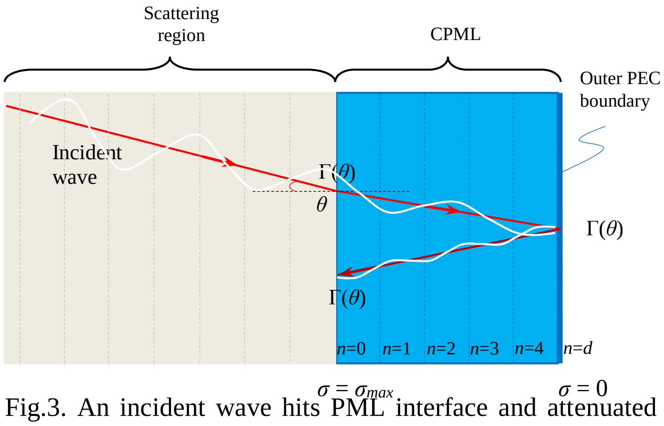


Fig.3. An incident wave hits PML interface and attenuated inside PML, reducing its amplitude. When it hits the end of PEC boundary, the wave is reflected and attenuated again.

In order to evaluate the quantity of the reflection due to the imperfectly PML boundary, an FDTD reference value is required to be computed with computational domain free from limited space reflection error where it extended 3 times the experimental setup [12]. Experimental reflection factor is the difference in reflection coefficient between the FDTD reference and the FDTD simulation with certain PML layer. Figure 4 shows that the minimum reflection error below 0.008 can be achieved with m = 4 and six PML layers for various conductivity, σ_{max} values. Overall, thicker PML will reduce the reflection error, nevertheless, it will cost more computation resources. The extent of reduction for FDTD reflection factor is less significant from ten to twelve PML layers compare to six and eight PML layers. In Figure 4, the theoretical factor, $\Gamma(\theta = 0)$ from (2) differs from experimental reflection factor due to the discretization error of the CPML.

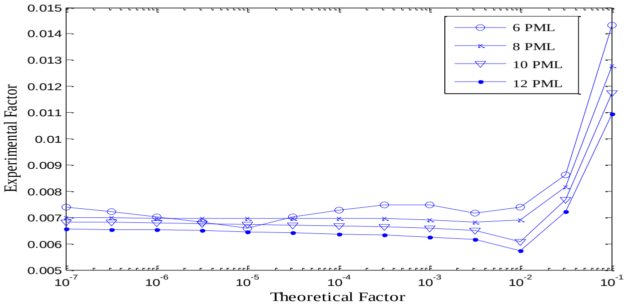


Fig.4. Experimental reflection factor as a function of theoretical reflection factor.

2.2. GUI of the studied simulator

The GUI of the study simulator is made up of a graphic display, six function buttons and a display drop down list as shown in Figure 5. The operational steps of the studied FDTD simulator are listed as:

1. "**Change Geometry Details**" button is used to define the grid size ($\Delta x = \Delta y$), background material properties, computational domain size (x and y) and number of CPML layers (n) as shown in Figure 6 (a).
2. "**Change Antenna Parameters**" button is used to define the monopole antenna's geometry dimensions and insulator's material properties as shown in Figure 6 (b).
3. "**Frequency-Domain Simulation**" button is used to define the type of excitation source signal ($V(t)$), operating frequency (f), characteristic time (τ_p), maximum number of time steps (N), amplitude source (V_o), and reflection factor ($\Gamma(\theta)$). The inputs entered are as shown in Figure 6 (c). It is capable of calculating the electric and magnetic field distribution in frequency domain.
4. "**Time-Domain Simulation**" button has similar defined parameters as "**Frequency-Domain Simulation**" button. This button will initiate real time animation of the electric field, ***E*** wave propagation.
5. "**Calculate Impedance**" button is used to calculate variation of impedance, Z_{in} with frequency, f. Parameters to be defined are range of frequencies (f_{min} and f_{max}), maximum number of time steps (N), and type of source ($V(t)$).

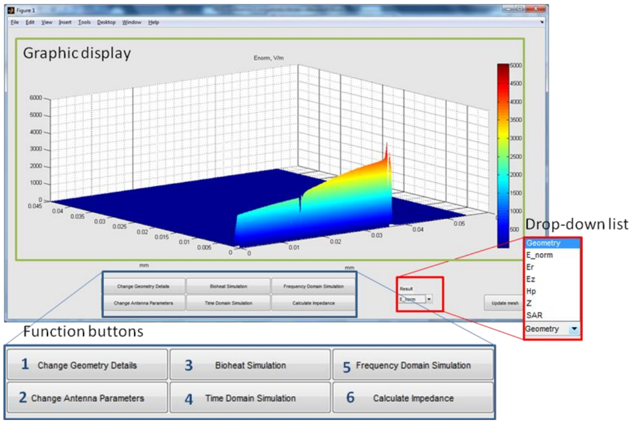
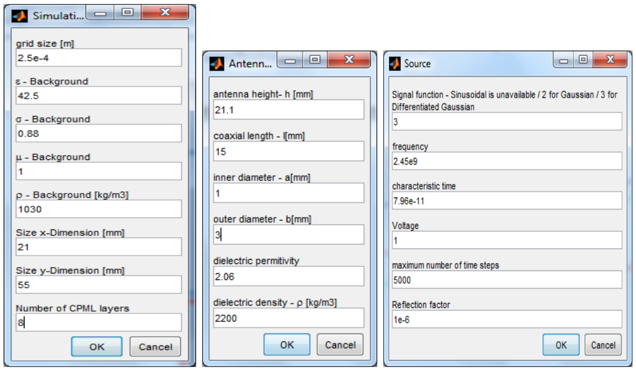


Fig.5. Developed simulator's GUI components.



grid size [m]
2.5e-4
ε - Background
42.5
σ - Background
0.88
μ - Background
1
ρ - Background [kg/m3]
1030
Size x-Dimension [mm]
21
Size y-Dimension [mm]
55
Number of CPML layers
8

antenna height- h [mm]
21.1
coaxial length - l[mm]
15
inner diameter - a[mm]
1
outer diameter - b[mm]
3
dielectric permitivity
2.06
dielectric density - ρ [kg/m3]
2200

Signal function - Sinusoidal is unavailable / 2 for Gaussian / 3 for Differentiated Gaussian
3
frequency
2.45e9
characteristic time
7.96e-11
Voltage
1
maximum number of time steps
5000
Reflection factor
1e-6

(a) (b) (c)

Fig.6. The dialog box of GUI.

The FDTD has been integrated with the FDM to provide thermal analysis of the RF monopole. In fact, the electromagnetic radiation energy from the monopole can be used to generate thermal energy. The bio-heat equation (Pennes's equation) has been used in FDM simulation in order to predict the heat distribution of the RF monopole which is surrounded by a lossy medium. The specific absorption rate (SAR) distribution of the lossy medium in FDM simulation was obtained from the previous FDTD simulation. The heat diffusion in the monopole is normally applied on the medical hyperthermia treatment. Thus, the studied simulator had included "**Bioheat Simulation**" button which is used to define the thermal properties of the biological specimens.

3. Results and discussions

A multi-layers insulated monopole as shown in Figure 7, is simulated using studied simulator for validation. The multi-layers insulated monopole is capable of producing lower reflection coefficient and large heating region compared to single-layer insulated monopole [13]. The parameters defined in the simulation are listed in Table 2. Typically, the normal electric field, E_{norm} is more concentrated near the surrounding of the conductor of monopole and it will be attenuated rapidly with the distance from the surface of conductor. For this reason, the normal electric field, E_{norm} distribution in logarithm scale is plotted in Figures 8 (a) and (b) in order to provide a better contrast visualization at 2.45 GHz.

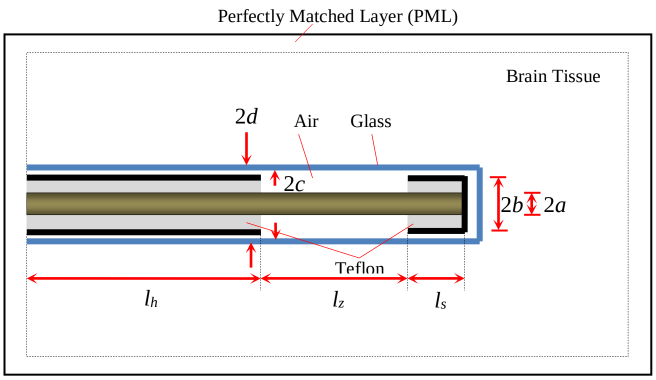
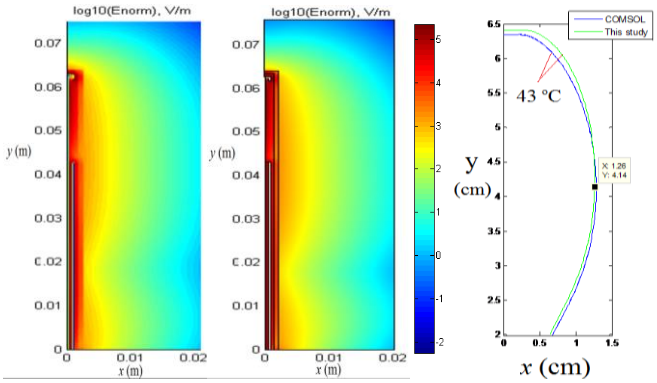


Fig.7. The cross-sectional view of multi-layers insulated monopole.

Table 2: Parameters defined in FDTD simulation.

Dim	Value (mm)	Dielectric Properties (at 2.45 GHz)		Thermal Properties (at 36.7 ˚C)	
a	0.145	Air	$\varepsilon_r = 1$	Brain	K =0.497 W/(m˚C)
b	0.60	Teflon	$\varepsilon_r = 2.1$		ρ =1030 kg/m^3
c	1.15	Glass	$\varepsilon_r = 5.1$		C_ρ =3600 J/(kg˚C)
d	2.10	Brain	$\varepsilon_r = 52.7$	Blood	K =0.45 W/(m˚C)
l_h	21.1		σ=13.3 S/m		ρ =1060 kg/m^3
l_z	18.75				C_ρ =3960 J/(kg˚C)
l_s	0.60				ω_b =0.0036 m^3/(kg.s)



(a) (b) (c)

Fig.8. Logarithm E_{norm} field distribution in brain tumor at 2.45 GHz. (a) Studied FDTD-based simulator. (b) FEM-based COMSOL simulator. (c) Comparison of temperature contour at 43˚C with COMSOL simulation.

Clearly, the simulated E_{norm} distribution looks broadly the same as the results obtained from COMSOL simulator. For FDM simulation, the temperature contour line at 43℃ is calculated by studied simulator and COMSOL simulator as shown in Figure 8 (c). The contour shows a rugby ball shape with major radius of 1.26 cm in radial direction, x. Overall, the temperature contour calculation by both simulators agrees consistently.

The calculated return loss (in dB) at excitation plane using studied simulator, COMSOL and literature data [13] was found to be closed at 2.45 GHz as shown in Figure 9. The slight deviation observed may be caused by different mesh type and boundary conditions used by different method.

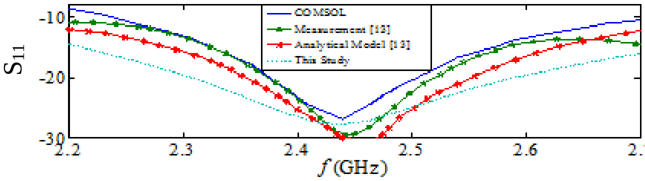


Fig.9. Comparison of calculated return loss (dB)

4. Conclusion

The MATLAB codes for the FDTD and FDM routines of this study can be downloaded for free from https://www.researchgate.net/publication/317100358_Commercial_and_Open_Source_Electromagnetic_Simulators_for_Education_Research_and_Industrial_Design_MATLAB_Codes. The accuracy and speed of computing using open source EM software are significantly good in which relative to the performance of costly commercial software. Hence, the existence of open source EM software appeared to be a huge challenge for the commercial EM software business. However, in terms of functionality and visualization, commercial EM software is far ahead compared to the open source EM software.

References

[1] K. S. Yee, Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media, *IEEE Trans. Antennas Propagat.*, vol. 14, no. 3, pp. 302-307, May. 1966.

[2] R. F. Harrington, Matrix methods for field problems, *Proc. IEEE*, vol. 55, no. 2, pp. 136-149, Feb. 1967.

[3] P. P. Silvester, Finite element solution of homogeneous waveguide problems, *Alta Freq*., vol. 38, pp. 313-317, May. 1969.

[4] R. G. Kouyoumjian and P. H. Pathak, A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface, *Proc. IEEE*, vol. 62, no. 11, pp. 1448-1461, Nov. 1974.

[5] T. Weiland, A discretization method for the solution of Maxwell's equations for six-component fields, *Electron. and Commun. AEU*, vol. 31, no. 3, pp. 116–120, 1977.

[6] T. Cao, X. Zhao, F. M. Soares, N. Tessema, and A. M. J. Koonen, 38-GHz millimeter wave beam steered fiber wireless systems for 5G indoor coverage: architectures, devices, and links, *IEEE Journal of Quantum Electronics*, vol. 53, no. 2, pp. 8000109, Feb. 2017.

[7] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method, *Comput. Phys. Commun.*, vol. 181, no. 3, pp. 687-702, 2010.

[8] T. Liebig, A. Rennings, S. Held, and D. Erni, openEMS-a free and open source equivalent-circuit (EC) FDTD simulation platform supporting cylindrical coordinates suitable for the analysis of traveling wave MRI applications, *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 26, no. 6, pp. 680-696, 2013.

[9] C. Warren, A. Giannopoulos, and I. Giannakis, gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar, *Comput. Phys. Commun.*, vol. 209, no. 12, pp. 163-170, 2016.

[10] F. Hacıvelioğlu, M. Alper Uslu, and Levent Sevgi, A MATLAB-based virtual tool for the electromagnetic wave scattering from a perfectly reflecting wedge, *IEEE Antennas and Propagation Magazine*, vol. 53, no. 6, pp. 234-243, 2011.

[11] J. G. Maloney, G. S. Smith, and W. R. Scott, Accurate computation of the radiation from simple antennas using the finite-difference time-domain method, *IEEE Trans. Antennas Propagat.*, vol. 38, no. 7, pp. 1059-1068, 1990.

[12] J. P. Berenger, Perfectly matched layer for the FDTD solution of wave-structure interaction problems, *IEEE Trans. Antennas Propagat*., vol. 44, no. 1, pp. 110-117, 1996.

[13] H. R. Ahn, and K. Lee, Capacitive-loaded interstitial antennas for perfect matching and desirable SAR distributions. *IEEE Trans. Biomedical Engineering*, vol. 53, no. 2, pp. 284-291, 2006.

Kok Yeow You was born in 1977. He obtained his B.Sc. Physics (Honours) degree in Universiti Kebangsaan Malaysia (UKM) in 2001. He pursued his M.Sc. in Microwave at the Faculty of Science in 2003 and his Ph.D. in Wave Propagation at the Institute for Mathematical Research in 2006 in Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia. Recently, he is a senior lecturer at Communication Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia. His main personnel research interest is in the theory, simulation, and instrumentation of electromagnetic wave propagation at microwave frequencies focusing on the development of microwave passive devices and sensors for medical and agricultural applications.

Chia Wui Lee was born in 1985. He received B.Eng degree in Mechanical Design Engineering from University Malaya (UM) in 2009. He received M. Eng degree in Electrical Engineering (Numerical Electromagnetics) from Faculty of Electrical Engineering, University Technology Malaysia (UTM) in 2015. Currently, he is a software engineer in automotive industry.

Chia Yew Lee was born in 1988. He received the Bachelor's degree in Electrical Engineering (computer) from Universiti Teknologi Malaysia (UTM), Skudai, Malaysia, in 2012. He pursued his Ph.D. in Microwave Medical Instrument at the Faculty of Biosciences & Medical Engineering in 2017 in UTM.