Shore to Ship Steerable Electromagnetic Beam System Based Ship Communication and Navigation

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Abstract **─** Electromagnetic waves prove to be a common ground for producing integrated systems that use a single transmitter, receiver, and computer system to perform communication, navigation, and surveillance activities. A steerable beam array antenna serves to communicate from shore to a moving ship close to the harbor. In this paper, the communication system parameters are used also to navigate the ship to a predetermined harbor dock. Knowledge of the electromagnetic radiation pattern of the beam steering array antenna, the position of the ship, and the predetermined trajectory for the ship are used to create an on-line navigational system that is driven by the received communication signal power. The discrepancies in signal power measured and the expected received power are used as an indicator that the ship is not properly aligned to the transmitter beam peak point. This discrepancy that is obtained by a signal processor is used to reset the rudder angle through a PID controller. It is shown that this system successfully keeps the ship within the border lines of the trajectory that had been marked out to guide the ship to its harbor dock. Moreover, the antenna electromagnetic beam, like a torch, moves a step ahead of the ship along the trajectory, allowing for automatic navigation of the ship as the ship's rudder is activated to move the ship to keep within the antenna beam's half-power points.

Index Terms **─** Antennas, electromagnetic signal processing, controls, and ship steering.

I. INTRODUCTION

Major ports over the world, including the port Klang in Malaysia, are undergoing restructuring to increase ship handling capacity, merging separate and distant berthing docks for different operators into a single large housing of multiple berths, and to tighten security both underwater and on sea surface. In each one of these futuristic changes, electromagnetic-based systems are expected to play a major role from satellite or aircraft based surveillance to narrow beam antennas to track, communicate, and navigate ships and fast boats within a limited space of waters close to the port [1]. In this paper, we report an integrated system for communication and navigation of a ship using a single spectrum, array antenna radiated electromagnetic waves to carry information and to provide the required parameters to estimate the position of the ship, the direction of its travel, and the speed required by the ship controller to navigate the ship along a path to the dock, determined by the port control officers.

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Ship communication stations may communicate with other ship stations or coast stations primarily for safety, and secondarily for navigation, and operational efficiency. However, wireless communication is in general subject to phenomena such as electromagnetic interference, unintended wave reflections, and atmospheric effects, which may deteriorate the electromagnetic signal quality, leading to lower possible bandwidth and errors in the transmitted signal. Hence, analysis and comparison of the communication carriers that are used for ship-shore communication are necessary to expose strengths and weaknesses in the geographical areas where the electromagnetic carriers may be used, how they fulfill different communication needs, and so on [2, 3].

The skill and knowledge required to navigate a ship close to a harbor versus at sea is significantly different [4, 5]. In the middle of the sea, the ship may be guided by the satellite signal using super high frequency bands. However, a shore based system usually involves a harbor base station (BS) for ship-to-shore communication. The very-high frequency bands and ultra-high frequency bands are commonly known as line-of-sight transmission bands and can be used for land-to-ship communication [5-8]. These also lend themselves well to signal processing the mathematically well defined electromagnetic radiation to get narrow, steerable beams which may be used to estimate the parameters of ship motion needed for navigation. The computation of the line-of-sight electromagnetic communication beam strength at the ship's receiver antenna is used as the basis for automatic ship navigation.

II. DESIGN CONSIDERATIONS FOR SHORE-TO-SHIP COMMUNICATION

An array antenna is usually chosen for shore to ship communication [1, 9, 10] as we did here. The more the elements an array antenna has, the better the gain and quality of the received signal; nevertheless, in order to keep the cost to a minimum and to make the signal processor fast and less heavy on digital memory, a two- element array antenna has been chosen as the transmitter antenna. An analytical solution for the electromagnetic power radiated is assumed to be known, which is the case for a two element array antenna. There are several types of radiation pattern that can be formed using different phase excitations between adjacent elements such as broadside, end-fire, and even scanning phase radiation patterns. Since the communication between ship station and shore station focuses only in the front direction, the end-fire radiation pattern is a good choice as it gives no radiation towards the back (landside) of the antenna, causing no waste of energy or interference with land systems. As in wireless mobile communications [11, 12], the position of the mobile station, and hence the position of the ship itself, could be determined by the communication signal when appropriately processed using a mathematical model of electric field strength and the actual electric field (corrupted by noise) received on board the ship. This feature has not yet been incorporated into the communication-navigation system reported in this paper.

III. THE SCENARIO OF THE ELECTROMAGNETIC ENVIRONMENT

Figure 1 shows the ship moving close to the coast and being guided by the antenna radiation pattern from the shore to its destination. Beam-forming at the shore base station antenna is done to maximize the signal-to-noise ratio of the communication link, as well as guide the ship along the pre-planned trajectory towards the dock. The study on ship dynamics is compulsory in order to control the motion of the ship. A mathematical ship model is necessary when designing an adaptive autopilot ship steering controller. A mathematical model is developed based on Fig. 2. The ship's path is sketched out by the moving antenna beam, like a torch lighting the path ahead. The ship is moving in the same direction as the steered antenna beam and eventually it is guided by the antenna beam to the dock.

The ship is kept moving within the half-power beam-width of the base station antenna's radiation pattern so that the received signal strength is always within the 500 km and 1500 km track. The radiation energy outside the half-power region is assumed to be negligible. Thus, successive beam-forming is needed to assure that the ship is kept moving within the half-power region and successfully navigated to its destination. The fluctuations in the electromagnetic signal are used to control the rudder of the ship through a PID controller [13, 14]. Assumptions made to develop this basic integrated electromagnetic system included ignoring signal noise and disturbances caused by other ships and boats to navigation. The ship's propeller system, and hence the speed of the ship, are not taken into account. Further refined development of this new system to make it implementable in a busy harbor should take these factors into account.

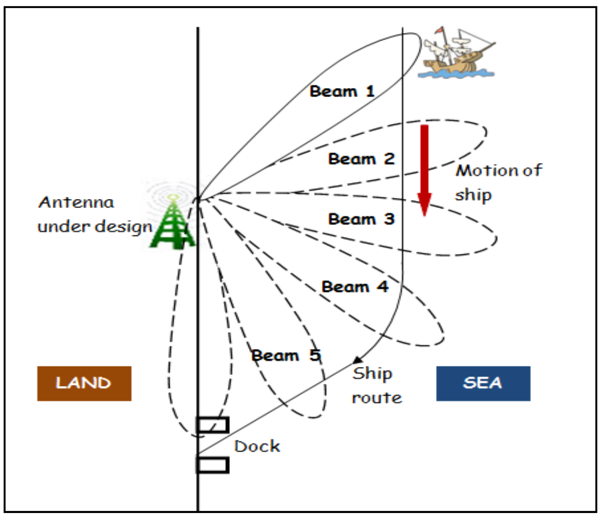
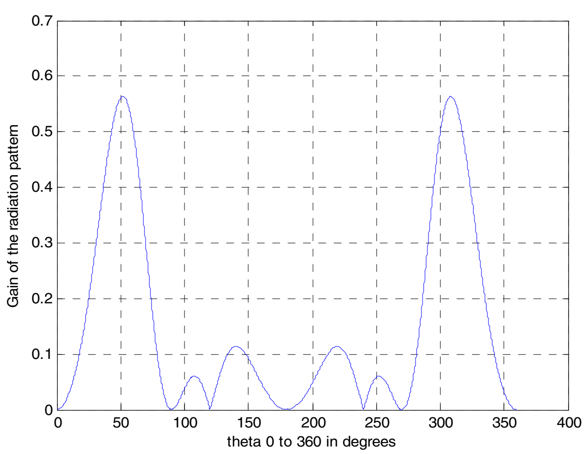
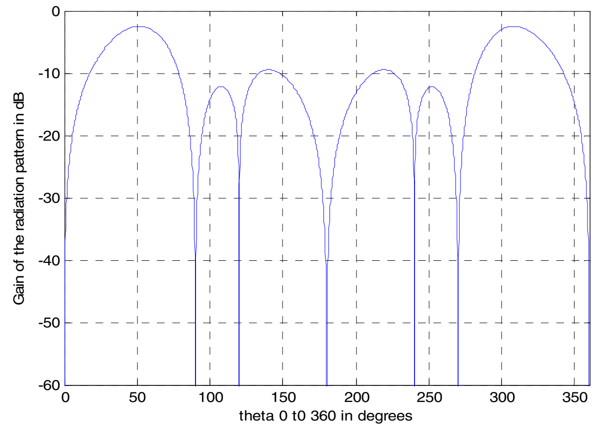


Fig. 1. Illustration of ship navigation system using antenna radiation pattern.



(a) Rectangular plot of the phase scanning array pattern.



(b) Rectangular plot of the phase scanning array in dB.

Fig. 2. Radiation plot of the phase scanning array in polar and rectangular forms.

In Fig. 2 the radiation pattern is given for the two element antenna when pointed 50^{o} away from the end fire axis. Although the beam-width is wide and side-lobes significant, for the specific scenario we considered without other interferers and signal noise, in the absence of other ships, the two element array was found adequate to steer the ship to its dock, keeping the ship within the specified track. The three tracks for which the integrated communication-navigation system was tested are shown in Fig. 3. In the first two cases the ship is initially outside the specified track, and the communication system must drive the ship control system to navigate it into the track, and then to the dock.

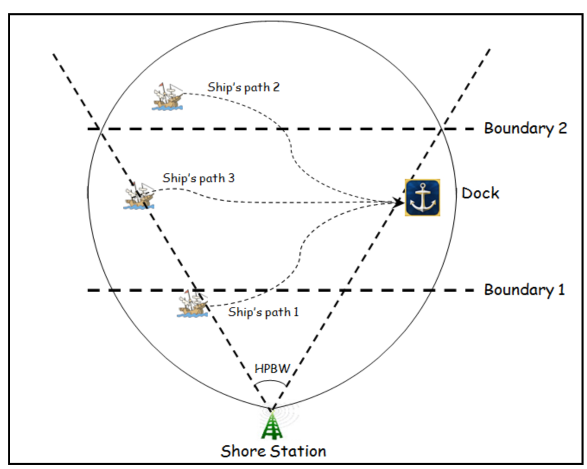


Fig. 3. Ship motion within the half-power beam-width.

In Fig. 3 we may also see the initial complex navigation, using the communication antenna, required to bring the ship to the straight forward trajectory once inside the two boundaries. The direction or turning angle of the ship will be different in order to guide the ship to the dock. The ship is being correctly guided as long as the ship is inside the half-power beam-width region. Two element end-fire array beam-forming is used as the shore-based base station guiding beam for the ship. There are two assumptions made: (a) The radiation energy outside the half-power beam-width is very low and is thus negligible; and (b) the radiation pattern is assumed to be uniform over the angle of the half-power beam-width.

IV. DYNAMICS OF SHIP NAVIGATION

The study on ship dynamics is compulsory in order to control the motion of the ship. A mathematical ship model is necessary when designing an adaptive autopilot ship steering controller. A mathematical model is developed based on Fig. 4, where (x_0, y_0) is the starting point of the ship, $\delta(t)$ is the instantaneous rudder angle, $(x(t), y(t))$ is the instantaneous position of the ship with respect to the coordinate system (X, Y), $\psi(t)$ is the heading angle at instant "t" with respect to the Y-axis, (x_G, y_G) is the heading position, $\psi_G(t)$ is the desired heading angle at instant "t" with respect to the Y-axis and V is the forward speed of the ship. The state of ship is defined by x(t), y(t), and $\psi(t)$ and its time derivative $\psi(t)$.

Now let r(t) be the desired turning rate of the ship. In this paper we have only considered the control of the rudder, and not that of the propeller [13]. Moreover, we have not considered collision avoidance in an environment in which other ships or boats may prove a threat to the ship [4]. The equations of motion in the discrete form are given by [13],

$$x(t+1) = x(t) + \Delta V \sin \psi(t) \tag{1}$$

$$y(t+1) = y(t) + \Delta V \cos \psi(t)\,, \tag{2}$$

$$\psi(t+1) = \psi(t) + \Delta\dot{\psi}(t), \tag{3}$$

and

$$\dot{\psi}(t+1) = \dot{\psi}(t) + \frac{\Delta(\mathrm{r(t)} - \psi(\mathrm{t}))}{\mathrm{T}}. \tag{4}$$

V. CONTROL SYSTEM FOR SHIP STEERING

The control system block diagram for a conventional controller is shown in Fig. 5. In the conventional ship steering controllers, the whole control system is developed for one set point. Hence, the controller is based on a linear model. In the PID controller design presented herein, the controller is developed using a varying set-point generator as indicated in Fig. 5. The set-point generator determines the desired heading angle at each state of the ship. At each point in the state space, the generator finds the desired heading with reference to the target point (destination). The controller input is the error obtained by comparing the present heading of the ship with the desired heading. With the variation of ship position coordinates (Fig. 4), the desired heading varies. Therefore, a desired heading generator is introduced into the system, which will determine the desired heading by looking at the target point.

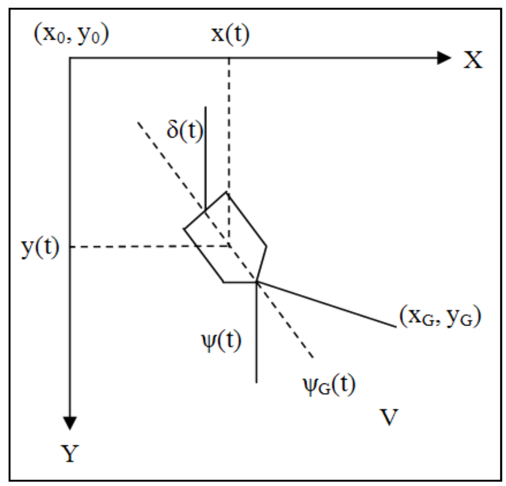


Fig. 4. Coordinates and notation used to describe the motion of a ship.

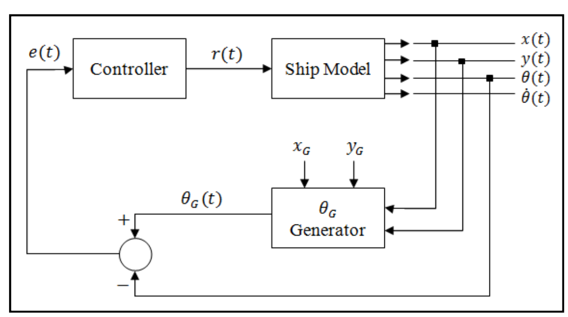


Fig. 5. Block diagram of the PID control system.

The design interface for a PID controller is determined by the following equations,

$$\theta_G = \tan^{-1}\frac{X_G - x(t)}{Y_G - y(t)} \quad (5)$$

$$e(t+1) = \theta_G - \theta(t+1)\,, \quad (6)$$

$$u(t+1) = \frac{k_I \times (e(t+1) + e(t)) \times \Delta}{2} \quad (7)$$

and

$$r = k_P \times e(t+1) + u(t+1) + \frac{k_D \times (e(t+1) - e(t))}{\Delta} \quad (8)$$

where θ_G is the set point generator output, and e(t) is the error of turning rate compared to the desired turning rate, θ_G. The PID controller output at instant t is given by,

$$r(t) = U_p(t) + U_I(t) + U_D(t), \quad (9)$$

where,

$$U_P(t) = K_P e(t) \quad (10)$$

$$U_I(t) = U_I(t-1) + K_I e(t), \quad (11)$$

and

$$U_D(t) = K_D \frac{(e(t) - e(t-1))}{\Delta}. \quad (12)$$

The large changes in the heading angle over the initial distances are due to the communication signal driving the ship back into its lane. Once inside the lane, it gradually settles at an angle of about 1^0 to keep it moving along the track as the moving transmission beam guides the ship smoothly along the track towards the dock.

Figure 6 shows the ship navigation for the ship path 2 shown in Fig. 3, where the position of the ship is initially beyond the second predefined boundary. The communication signals have to navigate the ship back into the path within which the ship needs to be kept and guided towards the dock. The ship control system will constantly adjust the heading angle of the ship by suitable turning. It is seen from Figs. 6 and 7 that the ship has been guided to its dock successfully.

Figure 7 shows the instantaneous heading angle with respect to the position of the ship for case 2. The heading angle in case 2 is always negative, thus the ship moves on in the downward direction until it reaches the dock. It can be seen that the heading angle of the ship changes significantly at the beginning. The changes in the heading angle get smaller and smaller until the desired heading angle is found for smooth guidance once the ship is back inside the predefined lane between 500 km and 1500 km; the changes in heading angle then become insignificant.

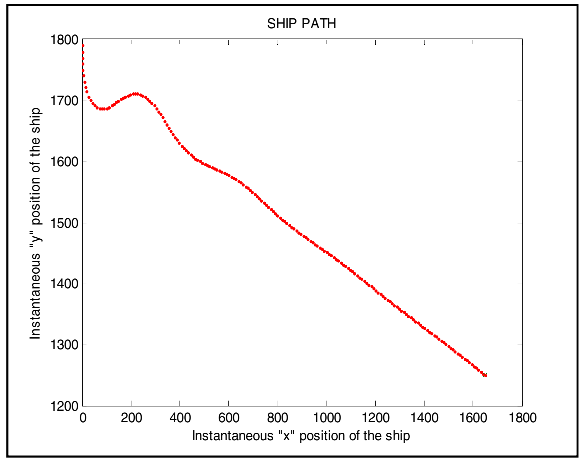


Fig. 6. Instantaneous position of the ship in km (Case 2 - ship on path 2).

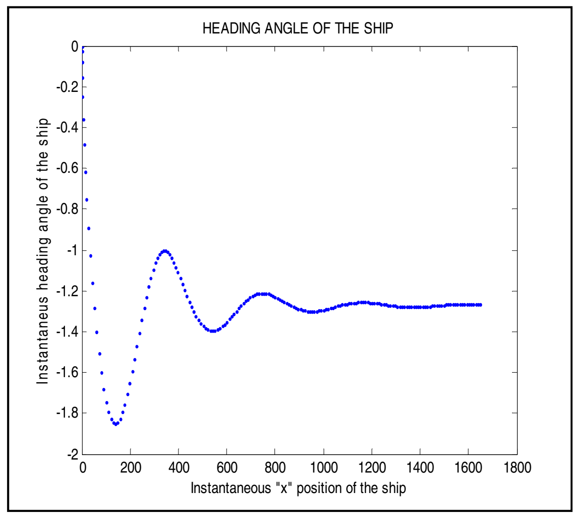


Fig. 7. Instantaneous heading angle of the ship against position 9 km (Case 2).

VI. COMBINED COMMUNICATION BEAM – PID SHIP CONTROLLER

In this section, we demonstrate the high performance of this communication beam based navigation by putting together the three new modules developed and reported in this paper:

(a) Adaptive, digital control of land to ship communication antenna beam. At present, all ship controllers use additional onboard and shoreline sensors to feed ship position and speed data to the PID controller. In this paper we report a new way of ship control, where the PID controller navigates the ship by using the shore to ship communication signals, without any extra sensors needed to trigger the PID controller action to change the rudder angle.

(b) The ship PID controller driven by antenna beam error correction.

(c) The computer simulated dynamics of a ship being guided by the integrated communication-navigation system, towards its dock in a harbor.

The ship's path is specified in a way that it will cross the two predefined boundaries as shown in Fig. 6. The ship will initially travel in an upwards direction until it passes out of the second boundary and the integrated system will automatically adjust the heading of the ship so that it is guided back in to the desired region. The ship will continue in the downwards direction and after it passes the first boundary, again it will be guided back into the lane bounded by the two boundaries. Eventually, it will reach its dock successfully.

Figure 8 shows the ship navigation for the integrated communication and navigation system. It is seen that the ship has been guided back into the lane when it passes the second boundary. The detection of the ship straying out of the safe track set to it is determined by measuring the power density of the signal received on board the ship. If the power density at the onboard communication receiver drops below a preset value, it is an indication that the ship has strayed out of the upper border line of the track. Similarly, if the received power density increases above a preset value, it is an indication that the ship is out of the lower boundary line of the track and is straying closer to the coastline. In either case the communication receiver triggers into action the control of the rudder to bring the ship back into the safe track. Furthermore, it is also seen in Fig. 8 that when the ship goes below the first boundary at about (700 km and 500 km) it has been guided back to the correct ship lane. The ship eventually reached its dock successfully.

Figure 9 shows the instantaneous turning rate of the ship for the communication-navigation integrated system. From the graph (where the angles are in radians), the largest positive turning rate is approximately 20° per second whereas the largest negative turning rate is -17.2° per second. The values of the largest positive turning rate and largest negative turning rate are beyond the limits. Although there are large turnings in the middle stage of the ship navigation, the overall performance has not been affected. The ship succeeded in getting its desired heading angle and reached its dock. In Fig. 7 it is seen that the turning rate remains nearly unchanging after the ship's desired heading angle is found. In this paper we have not taken into consideration the need not only to navigate the ship along the track set by the port authorities, but also to avoid collision with other ships or fast boats that may stray into its path. This aspect of navigation is not considered herein. We are addressing collision avoidance as a separate issue at this time, and at a later stage hope to connect it to seek a new system that integrates communication, navigation and collision avoidance all using a single system operating in a signal carrier and narrow bandwidth.

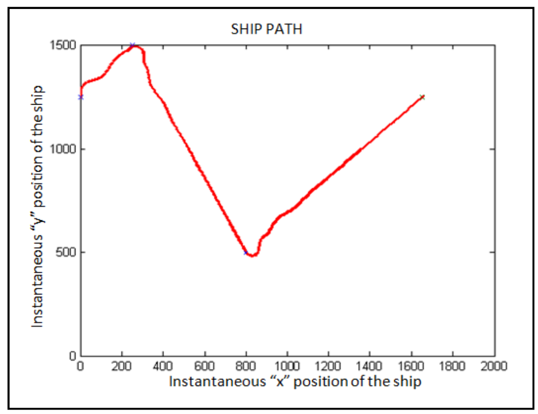


Fig. 8. Instantaneous position of the ship (guided by the integrated system).

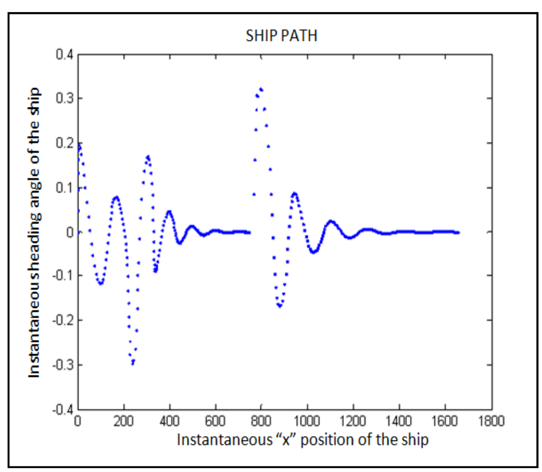


Fig. 9. Instantaneous turning rate of the ship (Integrated System).

VII. CONCLUSION

The main object of the integrated communication-navigation system was to develop a practical land-to-sea communication system using smart antennas, that would also navigate the ship to its dock (harbor destination). This was satisfactorily accomplished and tested for three different cases. For the ship communication system, a multi-element digitally beam steerable antenna is used in order to design a suitable land based communication system. An algorithm for keeping the ship within the half-power-beam-width (HPBW) has been developed, and as a further step, this algorithm has been used to navigate the ship along a prescribed path to its dock. The electromagnetic beam used for a shore to ship communication system was used successfully to perform two important functions of the navigation systems: (a) to step by step steer or show the ship the trajectory it should follow to get to the dock. The ship is kept close to the trajectory by making it move along the radiation beam to keep it at the center of the beam as the beam moves along the trajectory leading the ship. The ship's rudder is controlled by the variations in the transmitted power received on board the ship. (b) If the ship should stray away from the prescribed boundaries on either side of the trajectory, the marginal difference in the electromagnetic power received by the ship's communication receiver is used to control the rudder of the ship to guide it back to the trajectory and within the boundaries on either side of the trajectory.

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Paul R. P. Hoole was born in Jaffna, Sri Lanka in 1958. After having his basic schooling in Jaffna, he earned all his degrees, first degree to postgraduate, in the United Kingdom. He holds an M.Sc. degree in Electrical Engineering with a mark of distinction from the University of London and an M.Sc. degree in Plasma Science from University of Oxford. His PhD is from the University of Oxford. In his engineering career he has spent time in Singapore, Papua New Guinea, USA, Sri Lanka, and Malaysia. After a long career as a Professor of Electrical Engineering, because of his interests in lightning engineering, he has just embarked on a job as a Professor of Electrical and Electronic Engineering at

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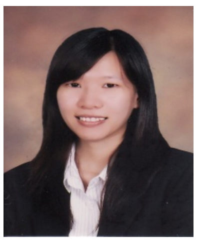
Prof. Hoole has authored several papers and books in engineering. His latest book (with K. Pirapaharan and S. R. H. Hoole), *Electromagnetics Engineering Handbook*, was released by WIT Press, UK, in June 2013. Beyond the time he devotes to engineering teaching and research, Prof. Hoole also spends time studying and teaching the Bible applied to contemporary times in seminaries and churches. He is married to a medical doctor, Chrishanthy, and they have three children: Esther, Ezekiel and Elisabeth.



Ong Syin Thon was born in a small town in Kedah, Malaysia in the year 1988. Her family, the Ong family, decided to move to an island which is known as Langkawi when she was six years old. Syin Thon's early education starts there from primary going on to secondary. She thereafter continued her pre-university studies for a year in Penang Matriculation College where her main discipline was Physics. She considers herself lucky to have been enrolled into University of Malaya, one of the top universities in Malaysia. Following four years' study majoring in the engineering field, she graduated in Telecommunications in 2011. This paper reports her research for her Telecommunication Engineering degree.

Ms. Ong's career as a software automation test engineer began at Motorola Solutions in Penang and was a valuable experience to her. She learned how important her role as an engineer is and ways to work and communicate with people in this big company. However, she decided to get herself a new career in Kuala Lumpur in order to stay closer to her friends and family. Thus, she became a software consultant at ISA Innovation, which is a small company but definitely a good place to learn new things related to software and solutions.

Ms. Ong enjoys learning new things. Outside of her profession, she wishes to learn a new language, a new musical instrument and so on. She is now in the middle of learning Japanese, hoping that perhaps someday she can travel to Japan without a tour guide.

S. Ratnajeevan H. Hoole, B.Sc. Eng. Hons Cey., M.Sc. with mark of distinction from London, Ph.D. Carnegie Mellon, is Professor of Electrical and Computer Engineering at Michigan State University in the US. For his accomplishments in electromagnetic product synthesis the University of London awarded him its higher doctorate, the D.Sc. (Eng.) degree, in 1993, and the IEEE elevated him to the grade of Fellow in 1995. Prof. Hoole has been Vice Chancellor of University of Jaffna in Sri Lanka, and as Member of the University Grants Commission there, was responsible with six others for the regulation of the administration of all 15 Sri Lankan universities and their admissions and funding. He has contributed widely to the learned literature on Tamil studies and been a regular columnist in newspapers. Prof. Hoole has been trained in Human Rights Research and Teaching at The René Cassin International Institute of Human Rights, Strasbourg, France, and has pioneered teaching human rights in the engineering curriculum.