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M1-D FDTD Methods for Mobile Interactive Teaching and Learning of Wave Propagation in Transmission Lines

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Abstract—This article presents the multiple one-dimensional finite-difference time-domain (M1-D FDTD) methods for mobile interactive teaching and learning of wave propagation in transmission lines. Both the M1-D explicit FDTD method and the unconditionally stable M1-D fundamental alternating direction implicit (FADI) FDTD method are discussed. Using the M1-D FDTD methods, multiple transmission lines, stubs and circuit elements can be simulated efficiently. They are readily implemented on mobile devices and applied for mobile interactive teaching and learning of transmission line topics including wave reflections from stubs, standing waves and impedance matching. These topics can be elucidated clearly through interactive visualizations on mobile devices. Using the unconditionally stable M1-D FADI-FDTD method, the simulation may be “fast-forwarded” with enhanced efficiency by using time step size larger than stability constraint. To gauge the students’ understanding of transmission line topics, educational survey and test conducted among students are also presented.

Index Terms—Mobile interactive teaching and learning, FDTD method, multiple 1-D method, electromagnetics education, wave propagation, transmission lines

I. INTRODUCTION

Transmission lines constitute one of the important topics in engineering electromagnetics (EM) which finds many applications in antennas and propagation, circuit design and electromagnetic compatibility, etc. However, wave propagation in transmission lines has always been challenging for many students to grasp due to both space and time dependence for traveling waves along the line. In many EM textbooks, the transmission line voltage and current equations are generally expressed in phasor form which has omitted the time dependency description. Many transmission line concepts and phenomena such as wave reflections, standing waves, impedance matching, stub resonances, etc. are rather difficult to elucidate using only mathematical equations in phasor form. All these while, efforts have been made by many to improve the teaching and learning of various EM topics through computer and simulation tools [1]-[4]. These tools usually provide visualization to students which help them better understand the underlying concepts in various EM topics. In [5]-[7], transmission line tools have been developed to aid students in understanding the fundamental concepts of transmission line. However, these educational tools are computer- or web-based which generally

lack touch-based interactivity and efficiency. Moreover, the requirement for computer or web connection greatly inhibits seamless teaching and learning anytime, anywhere.

The emergence of mobile devices over the years have allowed us to provide touch-based interactivity and visualization for students to enhance teaching and learning of EM. Furthermore, the wide availability of mobile devices among students has enabled seamless teaching and learning anytime, anywhere. Capitalizing on the affordances of mobile devices, we have previously developed mobile interactive apps to aid teaching and learning on topics such as EM polarization [8], plane wave reflection and transmission, etc. Here, the topics will be extended for wave propagation in transmission lines. To simulate wave propagation on mobile devices, efficient algorithms with minimal computing resources are required. Unfortunately, conventional EM computation method such as the popular 3-D full-wave finite-difference time-domain (FDTD) method [9] often calls for huge computing resources, thus it is difficult or unsuitable for mobile devices platform. To alleviate the difficulty, we have earlier proposed the multiple one-dimensional (M1-D) explicit FDTD method [10]. The proposed method simplifies the complexity of governing equations into multiple one-dimensional (M1-D) ones which are simpler and more concise. Hence, the M1-D FDTD methods are more manageable in terms of computing resources and are capable of running on mobile devices.

In this article, we present the M1-D FDTD methods for mobile interactive teaching and learning of wave propagation in transmission lines. In [11], the general features of our developed mobile interactive app *MuStripKit* have been described. The app allows quick initial design and analysis by engineers for various microwave circuits. Here, we shall detail how the app can be used effectively for mobile interactive teaching and learning of wave propagation in transmission line circuits. For the constructed transmission line circuits, the wave propagation can be simulated efficiently using the M1-D FDTD methods. Both the (conditionally stable) M1-D explicit FDTD method and the unconditionally stable M1-D fundamental alternating direction implicit (FADI) FDTD method will be discussed. They can be applied for mobile interactive teaching and learning of transmission line topics including wave reflections from stubs, standing waves and impedance matching. To gauge the students’ understanding of transmission line topics, educational survey and test conducted among them will also be presented.

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Fig. 1. Schematic of constructed transmission line circuit displayed on iPad screen.

II. MOBILE INTERACTIVE TEACHING AND LEARNING OF WAVE PROPAGATION IN TRANSMISSION LINES

In this section, mobile interactive teaching and learning of wave propagation in transmission lines are presented. Utilizing the mobile interactive app *MuStripKit* downloadable from App Store, instructor and students are able to construct circuits from various microstrip components on mobile devices. The components include microstrip transmission lines, short- and open-circuited stubs as well as lumped elements such as resistors, capacitors and inductors in parallel and/or series. Using the M1-D FDTD methods, the wave propagation in constructed transmission line circuits can be simulated efficiently on mobile devices. Fig. 1 exemplifies the schematic of constructed transmission line circuit displayed on iPad screen. For each transmission line, one can input/change the characteristic impedance Z_0 and the electrical length in degree θ or per guided wavelength λ_g . For the specified design frequency and dielectric constant, the physical width and length of the microstrip can be input/changed accordingly. Other useful parameters related to transmission line theory such as input (Z_{in}) and load (Z_L) impedances, input (Γ_{in}) and load (Γ_L) reflection coefficients, return and insertion losses are also displayed. Henceforth, teaching and learning of various topics on wave propagation in transmission lines are presented using clear time series which can be visualized interactively on mobile devices. The topics covered include wave reflections from short- and open-circuited stubs, standing waves and

Fig. 2. Electric and magnetic fields of the main TL and stub in M1-D FDTD method.

impedance matching. These topics can be elucidated clearly through interactive visualizations on mobile devices such as iPad and iPhone. With the aid of mobile interactive app, it provides ubiquitous visualizations for students anytime, anywhere.

A. M1-D Explicit FDTD Method for Mobile Interactive App

We shall first discuss the M1-D explicit FDTD method which is the main computational method for the mobile interactive app. Fig. 2 shows the electric and magnetic fields of the main transmission line (TL) and stub in M1-D FDTD method. The update equations for main TL and stub are given as [10], [11]

– Main TL:

$$E_x^m|^{n+1} = E_x^m|^n - \frac{\Delta t}{\epsilon} \frac{\partial}{\partial z} H_y^m|^{n+\frac{1}{2}} - \frac{\Delta t}{\epsilon} J_x^m|^{n+\frac{1}{2}} \quad (1a)$$

$$H_y^m|^{n+\frac{3}{2}} = H_y^m|^{n+\frac{1}{2}} - \frac{\Delta t}{\mu} \frac{\partial}{\partial z} E_x^m|^{n+1} \quad (1b)$$

– Stub:

$$E_x^s|^{n+1} = E_x^s|^n + \frac{\Delta t}{\epsilon} \frac{\partial}{\partial y} H_z^s|^{n+\frac{1}{2}} \quad (2a)$$

$$H_z^s|^{n+\frac{3}{2}} = H_z^s|^{n+\frac{1}{2}} + \frac{\Delta t}{\mu} \frac{\partial}{\partial y} E_x^s|^{n+1}. \quad (2b)$$

E_x^m, H_y^m are the electric and magnetic fields of the m -th main TL, E_x^s, H_z^s are the electric and magnetic fields of the s -th stub, n is the time index, Δt is the time step size, ϵ and μ are the permittivity and permeability which correspond to the transmission line characteristic impedance Z_0 and effective permittivity ϵ_{eff} . The spatial derivatives are discretized via central differencing operated on standard Yee cell.

The M1-D explicit FDTD method above consists of simple and efficient update equations for multiple transmission lines and stubs coupled at their intersections only. In particular, the fields at the intersection of main TL and stub are related via current density J as

$$J_x^m = -\frac{\partial}{\partial y} H_z^s. \quad (3)$$

In doing so, we are able to bypass the full-wave 3-D Maxwell's equations which are much more computationally intensive.

Fig. 3. Time series snapshots of wave propagation along main transmission line (aligned horizontally), short- and open-circuited stubs (aligned vertically).

Using the M1-D FDTD methods, multiple transmission lines, stubs and circuit elements can be simulated efficiently. Hence, they are readily implemented on mobile devices and applied for mobile interactive teaching and learning of wave propagation in transmission lines.

B. Teaching and Learning of Wave Reflections from Stubs

The wave reflections from short- and open-circuited stubs are first demonstrated for teaching and learning using mobile interactive app. Fig. 3 shows the time series snapshots of (E or voltage) wave propagation in transmission line circuit on iPad. The transmission line circuit consists of main transmission line (aligned horizontally), short- and open-circuited stubs (aligned vertically). Henceforth, Z_0 of the transmission lines and stubs are set at 50Ω unless specified otherwise. In Fig. 3(a), an incident Gaussian pulse is excited at the left end of main transmission line. The Gaussian pulse travels from left to right (with direction indicated by red arrow) towards the intersections of the main TL and stubs. As exemplified in Fig. 3(b), upon passing through the intersections, the waves are shown to have coupled into both stubs, traveling towards the respective terminations. Fig. 3(c) shows the waves reflected from the terminations of stubs. For the stub with short-circuit termination, the reflected Gaussian pulse has the opposite polarity as the incident pulse, while for the stub with open-circuit termination, it has the same polarity. They correspond to the reflection coefficients of $\Gamma = -1$ and $\Gamma = +1$, respectively.

Although only Gaussian pulse excitation is being depicted here, instructor and students are able to change the source excitations to sinusoidal wave types. (The sinusoidal wave sources are well suited for other topics such as standing waves and impedance matching to be demonstrated later.) The animations can also be paused and continued for clearer interactive visualizations. Such visualizations enable the students to better

understand the wave propagation along transmission lines as well as the wave reflections from short- and open-circuited stubs. With the aid of visualizations, they are also able to better relate the wave reflections from stubs to the respective reflection coefficients Γ 's.

C. Teaching and Learning of Standing Waves

Next, we shall demonstrate the standing waves resulted from short- and open-circuit loads on mobile interactive app. Standing waves are formed by interference (or superposition) between incident and reflected waves. Fig. 4 shows the time series snapshot of (E or voltage) wave propagation along transmission line terminated with short-circuit load. In Fig. 4(a), an incident sinusoidal wave is seen traveling from left to right (with direction indicated by red arrow) towards the short-circuit load. At that instant, the transmission line only contains incident wave and standing wave has not yet appeared. In Fig. 4(b), standing wave has begun to form in the superposed region as the reflected wave travels from right to left towards the source. Notice that the standing wave appears only around first cycle from the load end since it takes time for the reflected wave to travel further. As soon as the reflected wave overlaps with the incident wave, the resultant amplitude will be higher as is evident from the figure. After some time at steady state, Figs. 4(c)-(e) show that the reflected wave has superposed with the incident wave to form standing wave throughout the whole transmission line. While the incident and reflected waves are seen traveling in opposite direction, their superposition does not appear to be traveling. Instead, they oscillate with varying amplitude while standing between (dashed) null positions at the interval of $\lambda_g/2$ apart, just like the term 'standing wave' implies. Figs. 4(c) and (e) show the oscillation at (near) maximum amplitude, while (d) shows the oscillation at near zero amplitude. Furthermore, it can be observed that the amplitude of electric field (or voltage) at the

Fig. 4. Time series snapshot of wave propagation along transmission line terminated with short-circuit load.

short-circuit load corresponds to the first minimum (null/zero). The first maximum is located at $\lambda_g/4$ distance from the load end. All (dashed) maximas and minimas (nulls) are repeated at the interval of $\lambda_g/2$ apart along the transmission line.

Fig. 5 shows the time series snapshot of wave propagation along transmission line terminated with open-circuit load. The formation of standing wave is similar to that of the short-circuit load, except that the amplitude of electric field (voltage) at the open-circuit load corresponds to the first maximum. Subsequently, the first minimum (null/zero) is located at $\lambda_g/4$ distance from the load end. Again, all (dashed) maximas and minimas are repeated at the interval of $\lambda_g/2$ apart along the transmission line. Fig. 6 next shows the time series snapshot of wave propagation along transmission line terminated with matched $50\ \Omega$ load. The incident wave continues to be traveling from left to right and is absorbed by the matched load without being reflected. As exemplified in the figure, standing wave is not formed since there is no superposition of incident and reflected waves. From these visualizations, students are able to understand clearly the concept of standing

Fig. 5. Time series snapshot of wave propagation along transmission line terminated with open-circuit load.

waves being present or absent under short-circuit, open-circuit or matched loads. Instructors can also interactively change to other mismatched loads at the termination to demonstrate the corresponding wave reflections and resultant standing waves. In addition, it can be demonstrated to students that the standing waves are in fact oscillating and not “standing still”, as the term may imply. This would help to clear the possible misconception among some students, who may be misled by the ‘static’ sketch of standing wave envelope pattern as depicted in most textbooks.

D. Teaching and Learning of Impedance Matching

The mobile interactive app can also be used to aid teaching and learning of impedance matching using stubs and/or quarter wavelength transformer. Fig. 7 shows an example of single-stub matching network using short-circuited stub. The load that consists of resistor and capacitor has impedance $25 - j50\ \Omega$ at the design frequency 5 GHz. The matching network comprises a short-circuited stub of length l in parallel connection with a

Fig. 6. Time series snapshot of wave propagation along transmission line terminated with matched $50\ \Omega$ load.

Fig. 7. Impedance matching using a short-circuited stub.

series TL of length d . For this example, l and d are found to be $0.09\ \lambda_g$ and $0.063\ \lambda_g$ respectively to give Z_{in} as $50\ \Omega$. In Fig. 7, a Smith chart is also provided which depicts the traces of Γ_{in} (or normalized input impedance $z_{in} = Z_{in}/Z_0$) from point A to D as each component is cascaded in stages from the load end. When the impedance is matched, the end point D will be located at the origin corresponding to $\Gamma_{in} = 0$ or $z_{in} = 1$.

We next demonstrate the wave propagation in impedance matching network using quarter wavelength transformer at design frequency 5 GHz. The load is purely resistive with $100\ \Omega$ resistance and Z_0 of the quarter wavelength transformer is found to be $70.71\ \Omega$. Fig. 8 shows the time series

Fig. 8. Time series snapshot of wave propagation in impedance matching network using quarter wavelength transformer.

snapshot of wave propagation along transmission lines when the impedance is matched. In Fig. 8(a), an incident sinusoidal wave of frequency 5 GHz is traveling towards the quarter wavelength transformer and load. At steady state, one can visualize from Fig. 8(b) that there is no reflection from the quarter wavelength transformer and load since the impedance has been properly matched. Such visualization enhances the students' understanding of impedance matching and wave propagation along transmission lines with matched impedances.

E. M1-D Fundamental Alternating Direction Implicit FDTD (M1-D FADI-FDTD) Method

In all previous demonstrations, the M1-D explicit FDTD method has been adopted. It is a conditionally stable method with time step size restricted by Courant-Friedrichs-Lewy (CFL) stability constraint, i.e.

$$\Delta t \leq \Delta t_{\text{CFL}}, \quad \Delta t_{\text{CFL}} = \Delta / (v\sqrt{2}). \quad (4)$$

Here, Δ is the mesh size and $v = 1/\sqrt{\epsilon\mu}$ is the phase velocity of the transmission line. Note that Δt_{CFL} for M1-D FDTD method is more stringent than that of the pure 1-D FDTD method. The stability constraint limits the simulation efficiency and may at times require students' long wait for observing certain phenomenon which an instructor is trying to demonstrate, e.g. wave reflections from multiple long transmission lines terminated with mismatched load. The simulation may be "fast-forwarded" with enhanced efficiency using unconditionally stable FADI-FDTD method [12], [13], which allows time step size larger than CFL constraint. Note that such enhanced efficiency with larger time step size usually comes at the expense of reduced accuracy, which is still tolerable if only the concept visualizations (and not the exact values) are needed such as during teaching and initial design or analysis. The update equations of M1-D FADI-FDTD method for main TL and stub read [13]:

– Main TL:

$$\frac{1}{2}e_x^m|^{n+1} + \frac{\Delta t}{4\epsilon} \frac{\partial}{\partial z} h_y^m|^{n+1} = E_x^m|^{n+1} - \frac{\Delta t}{2\epsilon} J_x^m|^{n+1} \quad (5a)$$

$$\frac{1}{2}h_y^m|^{n+1} + \frac{\Delta t}{4\mu} \frac{\partial}{\partial z} e_x^m|^{n+1} = H_y^m|^{n+1} \quad (5b)$$

$$E_x^m|^{n+1} = e_x^m|^{n+1} - E_x^m|^{n+1} \quad (5c)$$

$$H_y^m|^{n+1} = h_y^m|^{n+1} - H_y^m|^{n+1} \quad (5d)$$

– Stub:

$$\frac{1}{2}e_x^s|^{n+\frac{1}{2}} - \frac{\Delta t}{4\epsilon} \frac{\partial}{\partial y} h_z^s|^{n+\frac{1}{2}} = E_x^s|^{n+\frac{1}{2}} - \frac{\Delta t}{2\epsilon} J_x^s|^{n+\frac{1}{2}} \quad (6a)$$

$$\frac{1}{2}h_z^s|^{n+\frac{1}{2}} - \frac{\Delta t}{4\mu} \frac{\partial}{\partial y} e_x^s|^{n+\frac{1}{2}} = H_z^s|^{n+\frac{1}{2}} \quad (6b)$$

$$E_x^s|^{n+\frac{1}{2}} = e_x^s|^{n+\frac{1}{2}} - E_x^s|^{n+\frac{1}{2}} \quad (6c)$$

$$H_z^s|^{n+\frac{1}{2}} = h_z^s|^{n+\frac{1}{2}} - H_z^s|^{n+\frac{1}{2}} \quad (6d)$$

where e_x^m, h_y^m are the auxiliary electric and magnetic fields of the m -th main TL, while e_x^s, h_z^s are the auxiliary electric and magnetic fields of the s -th stub. The other variables have the same definitions as those of M1-D explicit FDTD method above in (1)-(3). Note that unlike the conventional ADI-FDTD method, the right-hand sides of (5)-(6) in FADI-FDTD method are operator-free without any spatial derivative operator, which further improve efficiency.

To solve for electric fields on the main TL and stub, (5b) and (6b) are substituted into (5a) and (6a) respectively to yield the implicit update equations as

$$\begin{aligned} \frac{1}{2}e_x^m|^{n+1} - \frac{\Delta t}{2\epsilon} \frac{\partial}{\partial z} \left(\frac{\Delta t}{4\mu} \frac{\partial}{\partial z} e_x^m|^{n+1} \right) \\ = E_x^m|^{n+1} - \frac{\Delta t}{2\epsilon} \frac{\partial}{\partial z} H_y^m|^{n+1} - \frac{\Delta t}{2\epsilon} J_x^m|^{n+1} \end{aligned} \quad (7a)$$

$$\begin{aligned} \frac{1}{2}e_x^s|^{n+\frac{1}{2}} - \frac{\Delta t}{2\epsilon} \frac{\partial}{\partial y} \left(\frac{\Delta t}{4\mu} \frac{\partial}{\partial y} e_x^s|^{n+\frac{1}{2}} \right) \\ = E_x^s|^{n+\frac{1}{2}} + \frac{\Delta t}{2\epsilon} \frac{\partial}{\partial y} H_z^s|^{n+\frac{1}{2}} - \frac{\Delta t}{2\epsilon} J_x^s|^{n+\frac{1}{2}}. \end{aligned} \quad (7b)$$

When the spatial derivatives are approximated using central differencing operated on a standard Yee cell, the electric fields can be obtained by solving a set of tridiagonal matrices. Furthermore, the fields at the intersection of main TL and stub are related via current density J as

$$J_x^m = -\frac{\partial}{\partial y} H_z^s, \quad J_x^s = \frac{\partial}{\partial z} H_y^m. \quad (8)$$

Using the unconditionally stable M1-D FADI-FDTD method, the simulation may be “fast-forwarded” with enhanced efficiency by using time step size larger than stability constraint. It is worth noting that using large time step size for EM visualizations in education is fine as there is no need for high accuracy.

Besides *MuStripKit*, we have other apps which are developed based on the M1-D FADI-FDTD method. Fig. 9 shows the snapshot of wave propagation along short- and open-circuited stubs displayed by the FADI app on iPhone screen. Since the screen is typically smaller, the app is exemplified with pre-constructed schematic of short and open-circuited stubs which can be zoomed in/out and scrollable for clearer

Fig. 9. Snapshot of wave propagation along short- and open-circuited stubs displayed by the FADI app on iPhone screen.

demonstration to students. The opposite and same polarities of the reflected Gaussian pulse from short- and open-circuited stubs are again visible here. Contrary to previous demonstration, the animation here can be accelerated by adjusting the time step size using the slider. Note that the time step size is specified in terms of CFLN = $\Delta t / \Delta t_{\text{CFL}}$, e.g. CFLN = 20 in Fig. 9.

F. Educational Survey and Test

To gauge the students' reception of mobile interactive app and their understanding of wave propagation in transmission lines, educational survey and test have been conducted among 63 undergraduate students at School of EEE, Nanyang Technological University, Singapore. According to the survey, 98% of the students agreed strongly or moderately that the app is interesting and motivates them to learn more actively on topics of transmission lines. Furthermore, the students indicated an average rating of 8.6 out of 10 for the app in helping them to understand wave propagation in transmission lines. To assess the improvement of their understanding more quantitatively, pre- and post-tests have been conducted before and after the

usage of the mobile interactive app on iPad. The students were asked to sketch the voltage standing wave pattern on transmission line terminated with short- or open-circuit load. Before using the app, 43% of the students sketched the pattern correctly, with correct first minimum (null/zero) or maximum voltage at the termination depending on short- or open-circuit load. They were further asked if the standing wave is still oscillating, to which only 41% of them answered correctly as “Yes”. Based on the static sketch of voltage standing wave pattern in most EM textbooks, e.g. [14], it is probable to have such misconception among some students that the standing wave is “standing still” and static (not oscillating). After using the app, the percentage of students who sketched the pattern correctly increases to 94%, while 95% of them answered correctly that the standing wave is still oscillating. (5% of students still answered wrongly, probably because they still could not grasp the ‘wave’ concept on TMs for being used to DC or low-frequency operations on electrical wires.) Through visualizations such as depicted in Figs. 4 and 5, the first minimum or maximum voltage can be clearly identified by the students, along with the animation of oscillation. Overall, the app has generally received positive feedback from the students and it is promising to help improve their understanding of wave propagation in transmission lines.

III. CONCLUSION

This article has presented the M1-D FDTD methods for mobile interactive teaching and learning of wave propagation in transmission lines. Both the M1-D explicit FDTD method and the unconditionally stable M1-D FADI-FDTD method have been discussed. They have been readily implemented on mobile devices and applied for mobile interactive teaching and learning of transmission line topics. The topics covered include wave reflections from stubs, standing waves and impedance matching. Using the M1-D FDTD methods, the mobile interactive app provides ubiquitous visualizations for students anytime, anywhere. Based on the educational survey and test conducted among students, it is promising to help improve their understanding of wave propagation in transmission lines. In the near future, the app would be made available on Android platform to reach more users.

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