Development of a Mobile Application for Teaching Transmission Line Theory

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Abstract—The teaching of transmission line theory in electrical engineering courses must be tailored to an audience, which is increasingly reluctant to adhere to abstract disciplines. In our opinion, the best solution to make transmission line courses more attractive is to offer practical applications and intensively use of mathematical computer-aided teaching tools to overcome, at the beginning, the difficulties linked to the theory. Indeed, transmission line theory comes alive when the travelling waves are animated on a screen (smartphone, tablets, laptop, etc.). Fundamental concepts such as "progressive wave", "reflected wave" and "load matching" could be easily demonstrated in the classroom or at home. Transmission line simulations are applied to problems using connections to shunt, open, matched and unmatched loads, and show how the signal waveforms arise from one end to another. The proposed Android-based animations are used with a sinusoidal generator to illustrate the evolution to the sinusoidal steady state and allow learners to easily handle the corresponding Smith chart. Students are encouraged to run those applications at home as a computational laboratory to verify their solutions to homework problems.

This article introduces simple Android-based virtual tools for the investigation and visualization in real time of waves traveling along a terminated finite-length transmission line, without and with faults between the source and the load. The package can be used as an educational tool in various lectures or homework to aid teaching high frequency electronics and transmission lines theory.

Keywords—m-learning, transmission lines, waves propagation, high frequency electronics, Smith chart, FDTD method, Android

1 Introduction

Teaching high frequency (HF) electronics and transmission lines propagation is an increasingly challenging task. The major reason behind this is that many students feel that HF electronics is a difficult and demanding subject which require a good foundation in mathematics and involve different abstract phenomena [1]. This disinterest is paradoxical as our society deeply depends on electronic systems such as computer systems, mobile phones, communication networks, etc. Nevertheless, many initiatives have been proposed to search for new and more effective educational methods. Some are based on technology (virtual experiments [2-3] or real ones [4]), some are based on pedagogy and didactics and some on a mixed approach [5]. In this paper, we are leaning towards the first approach, which is the use of virtual experiment and simulation. The main goal is to allow students to visualize and give concrete expression to the abstract concepts taught in class.

The use of adequate laboratory experiments is a critically important aspect of education. Experience in teaching shows that a complementary approach, combining theoretical and practical exercises, is vital for an effective learning [6]. According to Hansen [7], students retain the most when they are able to manipulate, modify and control experiments related to the taught course, thereby putting into practice what they are learning.

On the other hand, the fast growth of mobile technologies such as smartphones, tablets and laptops as well as online applications and tools, has spurred our imagination as how education can be drastically transformed and improved through the use of such technologies. Mobile devices have transformed the way that people communicate, work and search for information. The challenge for researchers and educators was to explore how mobile technologies might be used to support learning [8].

Mobile learning is an area developing very quickly and has been considered as the future of learning [9]. Mobile devices enhance learning and provide access to learning resources in real time without any geographical restrictions. This flexibility makes it possible for learners to minimize their unproductive time, hence enhancing their studies balance. Technological progress can contribute significantly to the improvement and enhancement of learning, as handheld devices become cheaper, lighter, with better screen analysis, longer battery life and faster network speed.

In this scope, we introduce in this article a set of interactive applications in high frequency electronics and wave propagation for mobile learning that can be used both for educational and engineering purposes. The simulations were developed using the Finite Difference Time Domain (FDTD) numerical method. If used properly, these interactive applications would certainly increase teaching efficiency in classical and online lectures.

2 Transmission Line theory

At high frequency, transmission lines behave very oddly. In traditional circuit theory (low frequency), the transmission lines would not matter and the length of the wires connecting the components can for the most part be ignored (i.e. the voltage on the wire at a given time can be assumed to be the same at all points). However, for high-frequency transmission lines, the voltage changes in a time interval comparable to the time it takes for the signal to travel down the wire, the length becomes important and the wire must be treated as an influent component.

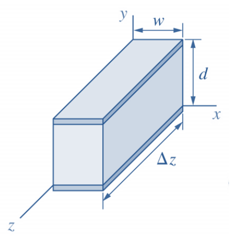
In the high frequency case, the length of the transmission line can significantly affect the results. To determine the voltage and current that flows in the circuit, we would need to know the source signal and the input impedance.

In communications and electronic engineering, a transmission line is a specialized structure designed to transport alternating current of radio frequency between two distant points, i.e. currents with a frequency high enough that their wave nature must be taken into account. Transmission lines are used for purposes such as connecting radio transmitters and receivers, antennas, computer networks, television cables, telephone switching centers, etc. Hence, a thorough understanding of subjects such as antenna theory, electromagnetic field/wave theory, wireless communication, etc. requires a deep understanding of transmission lines. If not, hooked up devices working with a length of transmission line at high frequency will lead to unpredictable behavior.

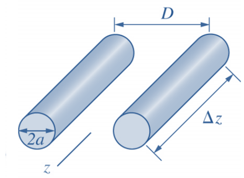
High frequency currents tend to reflect from discontinuities in the cable such as connectors and joints, and travel back down the cable toward the source [10]. If the length L of the transmission line significantly alters the input impedance Zin, then the current into the antenna from the source will be very small and a phase delay will be added. Those reflections act as bottlenecks, preventing the signal power from reaching the destination. To carry electromagnetic signals with minimal reflections and power losses, we often use specialized construction, and impedance matching.

Examples of common transmission lines include parallel line (ladder line, twisted pair), coaxial cable and planar transmission lines such as stripline and microstrip which commonly feeds patch/microstrip antennas (figure 1).

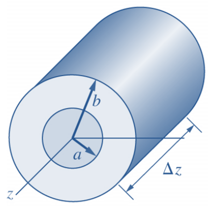
At microwave and above frequencies, power losses in transmission lines become excessive, and waveguides are used instead [11], which work as "pipes" to confine and guide the electromagnetic waves [12]. We also note that the theory of sound wave propagation is very similar mathematically to that of electromagnetic waves, so techniques from transmission line theory could also be used to build structures to conduct acoustic waves.



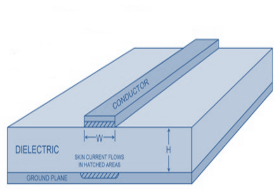
a) Parallel-plate line



b) Two-wire (twin-lead) line



c) Coaxial line



d) Microstrip line

Fig. 1. Types of transmission lines

3 Modeling of Transmission Lines

3.1 The electrical model

The simulation of wave propagation in transmission lines is based on the electrical model. A transmission line is more than a set of normal lines; it is a distributed parameter physical system. It is used in order to transmit electrical energy and signals from one point (called source) to another (called load). This could be a transmitter and an antenna, a television and a receiver, a coupler and a power meter, etc.

A typical transmission line is generally modeled as a finite number N of cascaded RLCG circuits. Each circuit models a segment of the transmission line having a length equal to the total length of the transmission line divided by N and, as illustrated in figure 2, have a set of characteristic primary parameters: a unit-length resistance R [Ω/m], an inductance L [H/m], a capacitance C [F/m], and an admittance G [S/m] from which the secondary parameters are derived: the characteristic impedance, the propagation constant, the attenuation constant and the phase constant. The output impedance of the generator and input impedance of the load, although specified in the electrical model as simple impedances, can be programmed to vary with some parameters in order to capture the effects of non-linear input and output characteristics. The number of segments N could be specified by the user, with the restriction that the propagation time in a segment should be smaller than one tenth of the rise time of the stimulus signal.

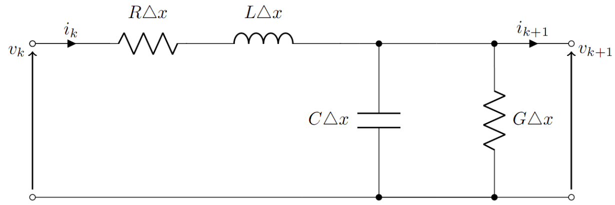


Fig. 2. The RLCG model of the k-th segment of the transmission line

For a uniform transmission line (along the x direction), the line voltage *v(x)* and the current *i(x)* can be expressed in the time domain as

$$\frac{\partial v(x,t)}{\partial x} + L\frac{\partial i(x,t)}{\partial t} + R\; i(x,t) = 0 \tag{1.a}$$

$$\frac{\partial i(x,t)}{\partial x} + C\frac{\partial v(x,t)}{\partial t} + G\; v(x,t) = 0 \tag{1.b}$$

And expressed in the frequency domain as

$$\frac{\partial V(x)}{\partial x} + (R + j\omega L)\; I(x) = 0 \tag{2.a}$$

$$\frac{\partial I(x)}{\partial x} + (G + j\omega C)\; V(x) = 0 \tag{2.b}$$

3.2 System of equations

The transmission line equations (eq.1 or eq.2) are the cornerstone to analyze the transient process of the transmission line [14]. Because of the limitations of the existing mathematical tools, it is rather difficult to find an accurate and perfect analytical solution of the transmission line equations. In this paper, we used the well-known Finite Difference Time Domain (FDTD) method to analyze the propagation characteristics of the signal and the transmission line and build our mobile applications.

The transmission line is divided into *N* equal segments of length Δx. In the same way, the total solution time is divided into *N* equal segments of length Δt. In order to provide the accuracy of the discretization, the voltage and current points are interlaced at alternating direction as v_1 , v_2 , v_3 ,…, v_{N+1}, and $i_{1/2}$, $i_{3/2}$, …, $i_{N+1/2}$. Each voltage and adjacent current solution point is separated by Δx/2. In the same way, each voltage time point and adjacent current time point are separated by Δt/2. The spatial-time grid of transmission line is illustrated in Figure 3.

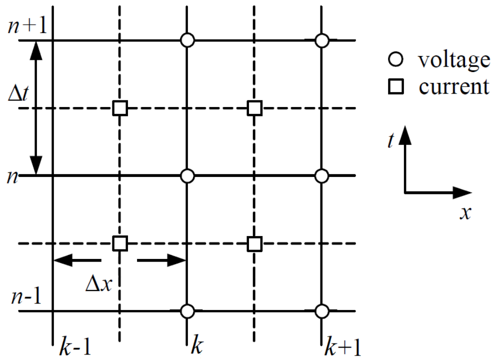


Fig. 3. Spatial-time grid used in the modeling of transmission lines

Fig. 4. Based on the FDTD method, the transmission line transient analysis iteration equations are simplified as

$$v_k^{n+1} = \left[\frac{\frac{C}{\Delta t}-\frac{G}{2}}{\frac{C}{\Delta t}+\frac{G}{2}}\right] v_k^n - \left[\frac{1}{\frac{C}{\Delta t}+\frac{G}{2}}\right] \frac{\left[i_{k+\frac{1}{2}}^{n+\frac{1}{2}} - i_{k-\frac{1}{2}}^{n+\frac{1}{2}}\right]}{\Delta x} \tag{3.a}$$

$$i_{k+\frac{1}{2}}^{n+\frac{1}{2}} = \left[\frac{\frac{L}{\Delta t}-\frac{R}{2}}{\frac{L}{\Delta t}+\frac{R}{2}}\right] i_{k+\frac{1}{2}}^{n-\frac{1}{2}} - \left[\frac{1}{\frac{L}{\Delta t}+\frac{R}{2}}\right] \frac{\left[v_{k+1}^n - v_k^n\right]}{\Delta x} \tag{3.b}$$

Those formulas connect the nodes of the voltages to the currents in between them. In this technique, a “leap-frog” scheme is used to simulate the voltage and current. To avoid interlacing, the voltages are updated at time n+1, and the currents are updated a half step later, at n+1/2.

The stability of the calculation is important since without a proper time step and/or a proper Δx, the iterations can quickly diverge to inaccurate results.

In general, the condition to insure stability of the FDTD method is:

$$\Delta t \le \frac{\Delta x}{v_{ph}} \tag{4}$$

where $v_{ph} = \frac{1}{\sqrt{LC}}$ is the phase velocity of the wave along the x direction.

The frequency and the total length of the line are also specified by the user, with the restriction that the space step should be smaller than one tenth of the minimum wavelength (eq. 5), in our algorithm; we used 20 space steps per wavelength as a default value.

$$\Delta x \le \frac{\lambda_{min}}{10} \tag{5}$$

4 Didactic Applications

4.1 Wave Propagation In A Transmission Line

Transmission line propagation is a mandatory topic in high frequency electronic education. In most cases, students have difficulties of intuitively perceiving the signal propagation in transmission lines, especially when reflections from unmatched terminations or impedance discontinuities are involved. The main cause of this problem comes probably from the inability to visualize the propagation phenomena, which is evolving simultaneously in time and space. To cope with this situation, we proposed a transmission line simulation that produces results in an animated fashion. Based on numerical solving of the Telegrapher's equations (eq.1), the proposed simulator is consistent with the physical phenomena and gives the students an intuitively insight of transmission line propagation.

The proposed wave propagation application is a multipurpose simulation designed for all Android OS and is based on the FDTD model described in the last section. The front panel of the App is given in Figure 4. There are five input data blocks on top of the panel. The user supplies the transmission-line parameters such as its length L, permittivity ε_r and attenuation A. The source parameters are automatically selected as a sinusoidal wave, but the user is able to change its frequency f. The last block on the right is used for the specification of the load Z_L. It may be a resistive load, a parallel combination of a resistor and a capacitor, or a serial combination of a resistor and an inductor, and serial/parallel resonant circuits. The user supplies the numerical values corresponding to each case. Once the user specifies all input parameters, the App instantly simulates the wave propagation inside the transmission line in the time domain. The user has the choice to either visualize the progressive wave, the regressive wave or the total wave via the *"ListView"* button at the top of the App.

The Figure 4 shows a screenshot of a sinusoidal wave propagation running in a transmission line of 50Ω. The figure on the left shows the simulation of a 2 m, loss-free homogeneous (uniform) transmission line, excited with a source wave of 800 MHz with a matched load of 50Ω. The result shows the real-time moving progressive wave along the line. The figure on the right shows the total wave along a 1GHz lossy line with an attenuation of 100dB/m and closed with a short-circuited load. The result shows a stationary signal with fixed nodes.

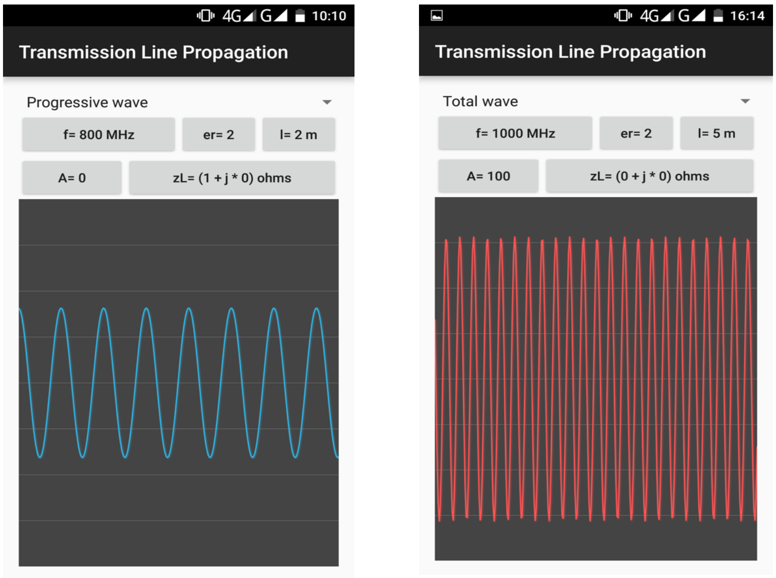


Fig. 5. The wave propagation in transmission line mobile application

4.2 Smith chart

Despite the advent of computers and numerical means, the Smith chart remains a very solicited didactic tools by teachers. The advantage of the Smith chart is its ability to pinpoint the reduced impedance and the reflection coefficient at any point of the line by simply drawing the circle between the center of the abacus and the reduced load impedance Z_L and moving along the circle. A complete lap corresponds to a wavelength of $\lambda/2$ and a half lap to $\lambda/4$. To be placed at other points, it is necessary to use the graduations of the outer circle, either in the direction "towards the source" or "towards the load".

The Smith chart App allows learners to take control of the tool in a simple and interactive way. The proposed application makes it possible to place any load Z_L on the chart, and design HF matching networks composed of lumped and distributed elements. Moreover, it allows the calculation of the input impedance Z_{in} and the reflection coefficient at the input Γ_{in} and at the output Γ_{out}.

Figure 5 illustrates the processes of impedance transformation. On the left, the chart shows how a 100Ω impedance (red point) is transferred through a transmission line of 0.4m length with an attenuation of 100dB/km until it reach the other end of the line (green point). The reflection coefficients and the reduced impedances of both points are displayed in the bottom of the screen. A sweep button is added to the application to observe the changes in the chart with the variation of each parameter.

This kind of application could also be used in a step by step matching process where the input impedance has to be transferred to the source terminals to represent a

50Ω load. The students have the choice between different kinds of matching process: single stub, double stub or RLC circuit and will be guided through the process.

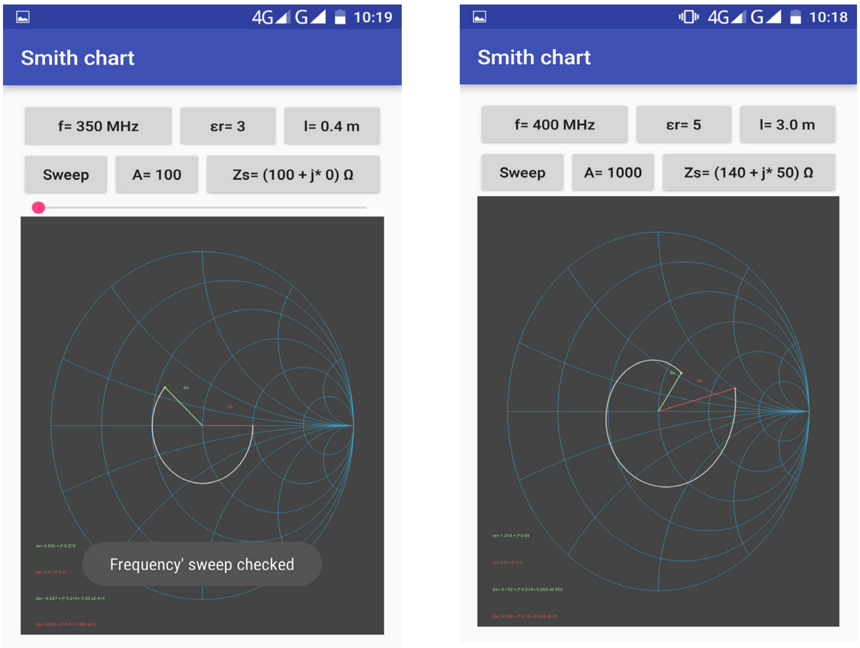


Fig. 6. The Smith chart application

5 Conclusion

An Android-based transmission line application set was introduced in this article. The package is designed to visualize wave propagation and reflections from various discontinuities along a transmission line and take in hand the use of the Smith chart. It may also be used as a matching process. The user may exercise tests, in real time, of different types of randomly selected terminations and faults, and may try to find out what kind of problem exists by analyzing the time domain simulated pulses. The application is a good virtual tool that can be used in both HF wave propagation electronics lectures as well as virtual laboratories.

The main advantages of this kind of interactive applications over existing simulations is that it provides animated real time results, showing the time evolution of the space domain solutions, which is a visual relevant representation of the propagation phenomena. This sort of mobile App will allow students to manipulate the equations to represent more complicated electrical models, hence, deepening their understanding of the taught subject. It also stimulates their participation and increases their motivation.

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