Computational Techniques for Design and Analysis of Time-Varying Capacitor Loaded Transmission Lines Using FDTD and Simulink

Anand Kumar, Graduate Student Member, IEEE, Jogesh Chandra Dash, Member, IEEE, and Debdeep Sarkar, Member, IEEE

Abstract—In this paper, MATLAB based computational approaches for the design and analysis of time-varying capacitor-loaded transmission lines using the finite-difference time-domain (FDTD) technique and the Simulink design environment are presented. The FDTD formulation for multiple lumped capacitors loaded in series on a transmission line is discussed and extended to include time variation of capacitance. The design methodology for the same is also discussed using MATLAB’s Simulink using the RF Blockset Library. The developed FDTD formulation and the Simulink method are then used to design a mixer with time-varying capacitors loaded transmission line.

Index Terms—Finite-Difference-Time-Domain, FDTD, space-time metamaterial, mixer, simulink.

I. INTRODUCTION

Computational modelling of materials has been progressively pursued with the development of computational techniques and EM modelling software applications. It gives designers the freedom to use an empirical approach and avoid detailed analysis while modelling intricate structures or materials with complex properties. While the designers and researchers exploit the power of computational techniques, research is being conducted to develop newer methods for better and easier modelling. In [1], the authors talk about techniques to model lumped circuit component terminations to model their EM behaviour in very high-speed digital systems to deal with the shortcomings of traditional SPICE solvers.

Space-time modulation of electrical circuit components of electromagnetic (EM) systems provides a unique potential to model the systems’ response in unusual ways, both in the time and frequency domains [2]. Recently, much attention has been given to the studies on “temporal modulation” [3] of radio and optical components. Time modulation of (effective) parameters of circuits components, transmission lines, media [4], [5], [6], [7], metasurfaces and metamaterials [8], [9], [10], can help overcome significant constraints such as impedance matching [11], bandwidth [12], reciprocity [13], [14], [15], and energy accumulation [16]. Space-time varying metamaterials (STM) have been implemented using time-varying capacitors arranged in parallel with the transmission line [17], [18]. Rigorous routines have been deliberated for the analytical formulation of STM systems in [17], [18], [19], [20]. Popular commercial EM solvers are limited by their inability to model circuit components (e.g. R, L, C) and material parameters (e.g. $\sigma$, $\mu$, $\epsilon$) as a function of time.

In this paper, the authors have used time-varying capacitors in series with the transmission line, allowing a more straightforward modelling approach using a simple FDTD formulation. In addition, a new alternative approach to model and simulate the space-time metamaterials is introduced in this paper using the new RF Blockset Library [21] of Simulink. This technique allows the designer to model space-time varying metamaterials on transmission lines by using appropriate blocks from the available libraries. The proposed FDTD and Simulink model is then extended to realize a transmission line-based mixer. To the best of authors’ knowledge time-varying capacitors loaded in series with the transmission line and the Simulink based block diagram approach for modelling time-varying circuits, have not been reported in the literature.

Formulation of FDTD update equations for a simple one-dimensional transmission line is presented in section II-A. The modified equations to include a series lumped capacitor on the transmission line are deliberated in section II-B. In section II-C, the modified unit cells formulated in section II-B are used to model a transmission line with multiple series lumped capacitors on a transmission line and the s-parameters using FDTD analysis are obtained. MATLAB’s Simulink based modelling of transmission line with lumped capacitors loaded in series is presented in Section III. The developed formulation is then altered to allow time variation of capacitance of the lumped capacitors loaded in series with the transmission line. It is observed that time modulation of capacitance cause mixing of the frequency of wave propagating through the transmission line and the capacitance modulation frequency. This observation
proposes the use of the above circuit configuration as a mixer. Therefore, the design of a mixer using time-varying capacitors is discussed in Section IV. In the subsequent subsections, the design of a mixer using time-varying capacitors loaded on a transmission line using the FDTD technique (Section IV-B) and Simulink method (Section IV-A) is discussed. The study of various parameters affecting the mixing is discussed in detail in Section V. Finally, a brief conclusion of the work is presented in Section VI.

II. FDTD MODELLING OF TRANSMISSION LINE WITH LUMPED CAPACITORS LOADED IN SERIES

A. Simple 1-D Transmission Line

The familiar equivalent circuit of an incremental section of a lossless and non-dispersive transmission line in one dimension is presented in Fig. 1. Where \( L \) is the inductance per unit length, and \( C \) is the capacitance per unit length transmission line. For this section of the line, the voltage and current on the line are expressed by a pair of coupled first-order differential equations, commonly known as the telegraphist’s equations:

\[
\begin{align*}
\frac{\partial i(z,t)}{\partial z} &= -C \frac{\partial v(z,t)}{\partial t}, \\
\frac{\partial v(z,t)}{\partial z} &= -L \frac{\partial i(z,t)}{\partial t}.
\end{align*}
\]

The definition of derivative is given by:

\[
\frac{\partial f(x)}{\partial x} = \lim_{\Delta x \to 0} \frac{f(x + \Delta x) - f(x)}{\Delta x}.
\]

The spatial-temporal Yee grid for FDTD update equations with \( \Delta z \) and \( \Delta t \) discretization in space and time, respectively, is shown in Fig. 2. \( k \) and \( n \) are used for indexing space and time, respectively. The FDTD update equations for voltage and current in a one-dimensional transmission line can be obtained by using (2) on (1). Hence, the update equation for voltage \((v)\) may be found as

\[
v_{k}^{n+1} = v_{k}^{n} - \beta \left( i_{k+1/2}^{n+1/2} - i_{k-1/2}^{n+1/2} \right).
\]

Similarly, the update equation for current \((i)\) is given by

\[
i_{k}^{n+1/2} = i_{k+1/2}^{n-1/2} - \gamma \left( v_{k+1}^{n} - v_{k}^{n} \right),
\]

where \( \beta = \frac{\Delta t}{\Delta z} \) and \( \gamma = \frac{\Delta t}{Z_{C} \Delta z} \).

For a transmission line with \( Z_{C} \) as the characteristic impedance and \( v_{p} = \frac{c}{\sqrt{\varepsilon_{r} \mu_{r}}} \) phase velocity, we evaluate \( L \) and \( C \) as

\[
\begin{align*}
L &= \frac{Z_{C}}{v_{p}}, \\
C &= \frac{1}{Z_{C} v_{p}}.
\end{align*}
\]

where \( c \) is the velocity of light in vacuum, \( \varepsilon_{r} \) is the relative permittivity, and \( \mu_{r} \) is the relative permeability of the dielectric medium in which the transmission line is placed. The parameters \( C \) and \( L \) in equations (5) may become frequency-dependent if \( \varepsilon_{r} \) or \( \mu_{r} \) is dispersive and the right-hand side of (1) will contain a convolution whose numerical solution could be necessary to obtain their discretized versions if \( C \) and \( L \) are frequency dependent.

A unidirectional (‘one-way’) source is fed at \( k_{source} \) by modifying the update equations (3) and (4) at the source cell location as

\[
v_{k_{source}}^{n+1} = v_{k_{source}}^{n} - \beta \left( i_{k_{source}+1/2}^{n+1/2} - i_{k_{source}-1/2}^{n+1/2} \right) + \left( \frac{v_{p} \Delta t}{\Delta z} \right) V_{inc,k_{source}+1/2},
\]

\[
i_{k_{source}+1/2}^{n+1/2} = i_{k_{source}+1/2}^{n-1/2} - \gamma \left( v_{k_{source}+1}^{n} - v_{k_{source}}^{n} \right) + \gamma V_{inc,k_{source}}^{n}.
\]

It injects the incident waveform \((V_{inc})\) only in the +z direction \((k > k_{source})\) at \( k = k_{source} \). The reflected wave can be observed within \( 0 < k < k_{source} \) [23]. Absorbing boundary conditions are applied at \( k = 0 \) and \( k = k_{j} \) to suppress reflections from the FDTD space boundaries [24]. Numerical stability is maintained by bounding the time step and satisfying the Courant’s condition [24], [25]

\[
\Delta t \leq \frac{\Delta z}{\sqrt{n_{dim} v_{p}}},
\]

where \( n_{dim} \) is the dimension of the simulation space.
B. Lumped Capacitor on Transmission Line

The FDTD model for the transmission line will now be modified to incorporate a lumped capacitor placed in series with the transmission line. Fig. 3 shows the revised incremental transmission line section with the added lumped series capacitor ($C_s$).

On applying KVL (Kirchhoff’s Voltage Law) and KCL (Kirchhoff’s Current Law) to the modified transmission line circuit with a series lumped capacitor ($C_s$) presented in Fig. 3, we obtain,

$$v(z + \Delta z, t) = v(z, t) - L\Delta z \frac{\partial i(z, t)}{\partial t} - v_{cs}(z, t), \quad (8a)$$

$$i(z + \Delta z, t) = i(z, t) - C\Delta z \frac{\partial v(z + \Delta z, t)}{\partial t}, \quad (8b)$$

where $v_{cs}(z, t)$ is the voltage across the lumped series capacitor,

$$v_{cs}(z, t) = \frac{1}{C_s} \int_{t_0}^{t} i(z, \tau) \, d\tau + v_{cs}(z, t_0). \quad (9)$$

Applying (2) to (8) we get the FDTD update equations for the transmission line unit cell shown in Fig. 3 as

$$v_{k+1}^{n+1} = v_k^n - \beta (v_k^{n+1/2} - v_k^{n+1/2}), \quad (10a)$$

$$v_{k+1/2}^{n+1/2} = v_{k+1/2}^{n-1/2} - \gamma (v_{k+1}^n - v_k^n) - \gamma v_{cs}^n (k + 1/2), \quad (10b)$$

where we calculate $v_{cs}^n$ by additional update equation

$$v_{cs}^n (k + 1/2) = v_{cs}^{n-1} (k + 1/2) + \frac{\Delta t}{C_s} v_{cs}^{n-1/2} (k + 1/2). \quad (11)$$

Equation (11) is obtained by approximating the integration in (9).

C. Multiple Capacitors on Transmission Line

The FDTD equations developed in section II-B for an incremental section of a transmission line with a lumped capacitor in series can be used to model multiple series capacitors on a transmission line. Fig. 4 shows the model FDTD space with a one-dimensional transmission line. The transmission line is loaded with series capacitors $s_1, s_2, \ldots, s_N$ with a gap ($g$) of 5 mm between the capacitors. The transmission line is 1 mm long, with one end at $z = 0$ (port 1) and the other at $z = l$ mm (port 2). The transmission line is modelled in a medium with relative permittivity ($\varepsilon_r = 4$) and relative permeability ($\mu_r = 1$).

The S parameter ($S_{21}$) for the transmission line loaded with capacitors is obtained by injecting a rectangular pulse in the frequency domain (i.e., sinc source in the time domain) and observing the spectral distribution of power of the signal at port 2. The sinc source introduced at $k_{source}$ is given by

$$V_{inc} = sinc \left( \frac{2\pi(n - n_0)\Delta t}{T_{bw}} \right) \quad (12)$$

where $T_{bw} = 1/f_{bw}$, and $f_{bw}$ is taken to be 50 GHz and $n_0$ as 100.

A Fast Fourier Transform (FFT) analysis is performed on the time domain reflected signal observed at port 1 and the received signal observed at port 2, respectively, when there are 5 ($=N$) series capacitors of 1 pF ($=C_s$) on the transmission line, and the spectral distribution is presented in Fig. 5. It can be observed that the transmission line, as expected, acts as a high pass filter with a cut-off frequency of 4 GHz.

III. MATLAB SIMULINK BASED MODELLING OF TRANSMISSION LINE WITH LUMPED CAPACITORS LOADED IN SERIES

MATLAB’s Simulink offers model libraries and a simulation engine for designing RF systems. Fig. 6(a) shows a simplified block diagram for a capacitor loaded in series with a transmission line, and Fig. 6(b) shows the Simulink circuit for Fig. 6(a). The microstrip transmission line block is available from the RF Blockset Library. RF Blockset Library provides import and output blocks to convert Simulink signals into RF Blockset compatible signals and vice-versa. Input signals from DSP sources are fed to the microstrip line via import, and received signals at the end are viewed in the spectrum analyzer via...
Fig. 6. (a) Block diagram for design of a transmission line with a series capacitor \( N = 1 \), and (b) the Simulink circuit for (a).

Fig. 7. Block diagram for an ideal mixer.

**outport.** Sine sources are available with Simulink libraries. A sine signal of frequency \( f_{op} \) is fed to the microstrip line loaded with series capacitors with capacitance \( C_s \). The circuit can be easily modified to increase the number of capacitors \( (N) \) loaded on the transmission line.

**IV. REALISATION OF A MIXER USING CAPACITOR LOADED TIME-VARYING TRANSMISSION LINE**

The block diagram of an ideal mixer is shown in Fig. 7. A mixer is an active or passive device that converts a signal from one frequency to another by modulating or demodulating a signal [26]. It has three signal connections or ports- the radio frequency (RF) input, the local oscillator (LO) input, and the intermediate frequency (IF) output. A mixer takes an RF input signal at a frequency \( f_{RF} \), mixes it with a LO signal at a frequency \( f_{LO} \), and produces an IF output signal that consists of the sum and difference frequencies, \( f_{RF} \pm f_{LO} \). A bandpass filter may follow the mixer and select the sum \( (f_{RF} + f_{LO}) \) or difference \( (f_{RF} - f_{LO}) \) frequency [26], [27].

**A. Simulation Using MATLAB’s Simulink**

The RF Blockset library in Simulink has blocks that can model lumped and distributed RF circuit elements. A simplified block diagram representation for a Simulink circuit with a time dependent lumped capacitor loaded on a transmission line is shown in Fig. 8(a). A sine source of frequency \( f_s \) is input to the MATLAB function block which computes the amplitude of the capacitance value \( C_s \) according to the following expression:

\[
C_s = 0.5(C_2 - C_1)(1 + u) + C_1 \tag{13}
\]

where \( u = \sin(2\pi f_s t) \) and \( C_1 \) and \( C_2 \) are maximum and minimum capacitance value of the capacitor. A special block for lumped capacitors with time and frequency-dependent characteristics is available from the RF Blockset Library. The capacitance \( C_s \) is modulated according to the function block. The received waveform at the other end of the microstrip line is observed in the spectrum analyzer. The Simulink circuit for Fig. 8(a) is shown in Fig. 8(b). A MATLAB function block is used to implement the function. The snippet of the MATLAB function is given below.

```matlab
1 function Cs = fcn(u)
2 C1=1; % in pF
3 C2=20; % in pF
4 Cs = (0.5*(C2-C1)*(1+u)+C1)*1e-12;
```

The variable capacitor available with RF Blockset has three pins- two for circuit connection and one for capacitance value.
This capacitance value is assigned with \( C_s \) and fed with the output from the MATLAB function block.

**B. Simulation Using FDTD**

In the developed FDTD formulation in Section II-C, the value of the capacitance \( C_s \) for the lumped capacitors is now periodically varied with time. The variation in the value of capacitance as a function of time is given as

\[
C_s = 0.5(C_2 - C_1)(1 + \sin(2\pi f_s n \Delta t)) + C_1
\]

where \( T_s = 1/f_s \) is the switching period, and \( f_s \) is the switching frequency of the sinusoidal variation of capacitance between \( C_1 \) and \( C_2 \).

A sinusoidal source of frequency \( f_{op} \) of 6 GHz is launched at \( k_{source} \) near port 1. The operating frequency at the source is to be chosen such that it is above the cut-off frequency of the transmission line circuit. In this paper, the analysis is focused on 6 GHz to support WiFi 6E (IEEE 802.11ax) applications. The wave launched at the source propagates through the transmission line with 5 \((= N)\) lumped capacitors separated by gap \((g)\) 5 mm with capacitance switching between two states \( C_1 = 1 \text{ pF} \) and \( C_2 = 20 \text{ pF} \) at frequency \( f_s \) taken to be 600 MHz as an initial value. FFT is performed at the time domain signals for the wave received at port 2, and the spectral distribution is presented in Fig. 9.

We observe that the received wave has new frequency components apart from \( f_{op} \), fed at the source. The newly generated frequency components correspond to \( f_{op} \pm qf_s \), for \( q = 1, 2, 3, \ldots \) and so on. Hence, switching the capacitance of the capacitors in series with the transmission line causes mixing of the source frequency \( (f_s) \) and the frequency \( (f_{op}) \) of wave propagating through it.

The conversion gain (or loss) of a mixer is defined as the ratio of the desired output signal power to the input signal power [26].

\[
G_c = 10 \log \frac{\text{available IF output power}}{\text{available RF input power}}
\]  

Conversion gain \( (G_c) \) for the transmission line configuration is plotted in Fig. 10. \( G_c \) is \(-3\) dB at 4.15 GHz and remains around 0 dB above 5 GHz. Hence, the realised mixer offers good conversion gain within the 5 to 10 GHz range.

The results in Fig. 9 obtained from the FDTD and the Simulink methods are in good agreement and the peaks of the modulated frequencies match exactly. The RF Blockset library’s blocks interact with other blocks of Simulink libraries via \textit{import} and \textit{output}, requiring parameters like carrier frequency, source/load impedance, and source type (voltage/current/power). Each of these parameters affects the simulation and the results. The slight mismatch in magnitude can be accounted to the differences in the computational approach in the FDTD technique and the new RF Blockset library of Simulink.

**V. PARAMETRIC ANALYSIS OF TIME-VARYING CAPACITOR LOADED TRANSMISSION LINE**

A number of physical parameters of the transmission line configuration can affect this signal modulation on the transmission line, such as the frequency of the source \( (f_{op}) \), the switching frequency \( (f_s) \) of the lumped capacitors, the contrast between the switching states of the capacitors \( (C_2/C_1) \), the number of such capacitors \( (N) \) and the gap between these capacitors \( (g) \). We perform a parametric study on each of the mentioned physical properties to analyze their effect on the frequency mixing.

**A. Variation of Source Frequency \( (f_{op}) \)**

The frequency of the source \( (f_{op}) \) is varied from 4 GHz to 10 GHz with the steps of 2 GHz when the switching frequency of the capacitors is maintained at \( f_s = 600 \text{ MHz} \). The transmission line has \( N = 5 \) lumped capacitors placed with a 5 mm gap \((g)\). The capacitors switch between \( C_1 = 1 \text{ pF} \) and \( C_2 = 20 \text{ pF} \). The spectral distribution for the received wave at port 2 obtained via FDTD is shown in Fig. 11(a). Transmitted signal at 2 and 4 GHz suffer attenuation as the transmission line with capacitors acts as a high pass filter with a cut-off frequency of 4 GHz. For source frequency above 4 GHz, the spectrum shows more power in the received signal at \( f_{op} \). It is also noticed that the power in the newly generated frequencies, i.e., \( f_{op} \pm qf_s \), decreases with an increase in the source frequency. The spectral distribution for the received signal using Simulink is shown in Fig. 11(b). The peaks for the frequencies and the trend in Fig. 11(a) and (b) are in good agreement.

**B. Variation of Switching Frequency \( (f_s) \)**

The switching frequency \( (f_s) \) of the capacitors added in series with the transmission line is parametrically varied from

![Fig. 9. Spectral distribution of the received voltage signal at the port 2 with time varying capacitors for \( g = 5 \text{ mm}, N = 5, f_{op} = 6 \text{ GHz}, f_s = 600 \text{ MHz}, C_1 = 1 \text{ pF} \) and, \( C_2 = 20 \text{ pF} \) via Simulink and the FDTD code.](image)

![Fig. 10. Conversion gain for \( g = 5 \text{ mm}, N = 5, C_1 = 1 \text{ pF} \) and, \( C_2 = 20 \text{ pF} \).](image)
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Fig. 11. Spectral distribution of the received signal at port 2 with time varying capacitors for \( f_{op} = 4, 6, 8 \) and 10 GHz when \( g = 5 \) mm, \( N = 5 \), \( f_s = 600 \) MHz, \( C_1 = 1 \) pF and, \( C_2 = 20 \) pF obtained via (a) FDTD method and, (b) MATLAB’s Simulink.

Fig. 12. Value of capacitance \( (C_s) \) with time for \( f_s = 300, 600, 900 \) and 1200 MHz.

300 MHz to 1.2 GHz with the steps of 300 MHz. The source frequency is 6 GHz, and the transmission line has \( N = 5 \) capacitors placed with a 5 mm gap \( (g) \) between them. The capacitors are switching between \( C_1 = 1 \) pF and \( C_2 = 20 \) pF. The variation of the capacitance with time for different switching frequencies is shown in Fig. 12. Fig. 13(a) shows the FFT of the transmitted signal at port 2. The received signals have the new modulated frequency components at \( f_{op} \pm qf_s \), and these new components vary accordingly with \( f_s \). Fig. 13(b) shows the spectrum of the received signal using Simulink. The frequency of the modulated peaks matches with Fig. 13(a).

C. Variation of Capacitance Contrast \( (C_2/C_1) \)

The effect of variation of the contrast between the switching states of the capacitors \( (C_2/C_1) \) on the transmission line modulation is studied. The 2nd state of the capacitance \( C_2 \) is varied when the source frequency \( (f_s) \) is 6 GHz and the switching frequency \( (f_{op}) \) of the capacitors is 600 MHz. The transmission line has \( N = 5 \) lumped capacitors placed with a 5 mm gap \( (g) \). Fig. 14 shows the value of capacitance \( (C_s) \) with time upon varying the capacitance contrast \( (C_2/C_1) \). Fig. 15(a) shows the spectral distribution of the received signal using FDTD. It is observed that when there is no change in capacitance, i.e., \( C_2/C_1 = 1 \), there is no modulation. When \( C_2/C_1 = 2 \), modulation is observed. The value of \( C_2/C_1 \) was then linearly varied from 1 to 30. The power transferred to the modulated peaks increases rapidly for lower values of \( C_2/C_1 \) and then saturates around \( C_2/C_1 = 5 \) and decreases very slowly on increasing \( C_2/C_1 \). Fig. 15(a) shows the spectrum of the received signal for \( C_2/C_1 = 1, 2, 5, \) and 20. Fig. 15(b) shows the spectrum of the received signal for variation of capacitance contrast using Simulink. The trend observed in Fig. 15(a) is the same in Fig. 15(b).

D. Variation of Number of Switches \( (N) \)

The number of switches, i.e., the switching capacitors, on the transmission line is increased from 1 to 7, and the received signal at port 2 is analyzed. The spectral distribution of the signal obtained by FDTD is presented in Fig. 16(a). The source
frequency \(f_{op}\) is 6 GHz, the switching frequency \(f_s\) of the capacitors is 600 MHz, and the lumped capacitors are placed with a 5 mm gap \(g\) between them. It is observed from Fig. 16(a) that the power delivered to the modulated frequencies at \(f_{op} \pm qf_s\) increases, and the power in \(f_{op}\) decreases with an increase in the number of switches on the transmission line. A similar trend is observed in the received signal spectrum using Simulink, shown in Fig. 16(b).

### E. Variation of the Gap Between the Switches \(g\)

The spacing between the switches \(g\) is parametrically varied from 3 to 6 mm, and the spectrum of the received signal at port 2 is shown in Fig. 17(a). The source frequency \(f_{op}\) is kept to be 6 GHz, and the switching frequency \(f_s\) of the capacitors is 600 MHz. There are 5 capacitors \(N\), and they switch between 1 pF \(C_1\) and 20 pF \(C_2\). It is observed from the spectrum of the received signal in Fig. 17(a) that the power in modulated frequencies increases with a decrease in \(g\). The observations from the spectrum of the received signals using Simulink in Fig. 17(b) agree with Fig. 17(a).

### VI. CONCLUSION

Computational techniques for modelling transmission line loaded with time-varying capacitors in series using the FDTD method and a new block diagram based approach using MATLAB’s Simulink is discussed. The FDTD formulation is developed by modifying the incremental section of the transmission line to incorporate a lumped capacitor, which is then used to model multiple capacitors on the transmission line with time-varying capacitance. Design methodology for RF circuits along with time-variation of lumped components using RF Blockset library of Simulink is then deliberated. Comparing results from the two techniques shows a similar trend and promising results. Further, the transmission line circuit with time-varying capacitors is then used to demonstrate working as a mixer. The effects of the various physical parameters on modulation in the mixer with a transmission line loaded with capacitors in series are studied.

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