Characterization and Measurement of Cable Losses Using Fractional-order Circuit Model

O. Aydin, B. Samanci and S. Ozoguz

Abstract—5G communication technology is used in very demanding applications, such as high-performance mobile devices, Internet of Things (IoT) applications, and wearable devices. Therefore, unlike the previous technologies, 5G technology requires massive bandwidth, mainly within three key frequency ranges, Sub-1 GHz, 1-6 GHz, and above 6 GHz. However, these challenges require more accurate and wide-band characterization of the circuits designed for 5G systems. To be specific, the losses, which can be neglected at lower frequencies, may substantially affect the performance of these circuits in the high frequency bands. This requires a comprehensive understanding and proper characterization of the loss mechanism within all frequency band of 5G. This paper investigates the viability of using the most common and easily accessible material FR-4 in circuits designed for 5G applications, and thus focuses on the proper modeling of the microstrip lines built around FR-4. For this purpose, we have used the fractional-order model of the lossy dielectric material, and ended up with a more accurate and simple model which fits well within a wide frequency range, from 1GHz to 16GHz.

Index Terms—Fractional-Order Calculus, 5G Communication Technology.

I. INTRODUCTION

As a result of very demanding specifications of 5G systems, a comprehensive understanding and proper modeling of electrical circuits designed for this technology are required. On the other hand, due to the interdisciplinary nature of fractional calculus, there has been a growing research interest in using fractional-order calculus as a powerful tool in biochemical, medical and electrical engineering applications. In biomedical systems, it is shown that the accurate modelling of the biological cells and tissues require the utilization of fractional-order calculus [1-3].

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In another implementations, there are two types of the fractional-order memristor: the capacitive and the inductive fractional-order memristor [4]. Fractional order circuits for emulating the mechanical impedance model of the human respiratory system is discussed elsewhere [5].

The fractional-order model calculus is also applied to the modeling of electrical circuits. Among these, the fractional-order model of transmission lines are presented in [6-7] based on the RLGC model approach. Basically, two main approaches have been presented for the RLGC based model of transmission line in the literature. In the first approach, the loss elements, which are due to the skin effect of the line and the dielectric absorption, are modeled by the serial resistance of the copper, R and the conductance G. However, this integer-order model produces inaccurate results and seem to characterize the transmission line loss for only high loss cases, where the main source of nonideality is due to the dispersion of the dielectric material [8].

On the other hand, fractional-order mathematical models developed for the reactive circuit elements, may provide more accurate representation of the electrical characteristics. The use of the fractional-calculus concept leads to the fractional-order RLGC model of the transmission line, where the involved inductor and capacitor are used as the fractional-order elements. In this model, fractional inductance is employed to model the skin effect, while the fractional order capacitance is used to model various nonidealities related to the dielectric [3, 5]. Following up in this direction, we use the fractional order model to characterize the FR-4 PCB loss to obtain more accurate model of this easily accessible element in the hope of using this element in wide bandwidth 5G applications.

In this paper, we have studied the proper modeling of the most common and widely available material FR-4, which offers reduced cost but suffers from higher loss. This may be useful in designing low-cost circuits for 5G technology built around high loss PCB materials. The fractional-order model provides higher accuracy and incorporates less number of model parameters. RLGC parameters of both models can be extracted from the measurement data. The evaluations of the models are performed based on a design of a microstrip transmission line with FR4 substrate with permittivity 4.4, substrate height of 1.0mm and loss tangent of 0.025 at microwave frequencies between 1 to 16 GHz. This paper is organized as follows: Section II describes the fundamental concepts related to the modeling of Transmission Lines. In Section III, the results and the comparison of the conventional
integer-order and fractional-order models are given. Finally, the conclusion is presented in Section IV.

II. TRANSMISSION LINE MODELS

II. 1 Conventional RLG C Model of the Transmission Line

Fig. 1(a) shows the Transmission Line model for integer order model. Per-unit model parameters can be given explicitly as follows:

\[
\begin{align*}
R &\approx R_0 + R_s \sqrt{1 + i} \\
L &\approx L_0 \\
C &\approx C_0 \\
G &\approx G_0 + G_d w
\end{align*}
\]

where \( f \) is the frequency in Hz, \( R_0 \) is the DC resistance of the line, \( R_s \) is the skin-effect resistance term, \( G_0 \) is the DC shunt conductance and \( G_d \) is the conductance used to model dielectric-loss [9, 10].

According to the model, the propagation constant (\( \gamma \)) and characteristic impedance (\( Z_0 \)) of the transmission line are defined as [10]

\[
Z_0 = \frac{R + j\alpha L}{\gamma} = \sqrt{(R + j\omega L)/(G + j\omega C)}
\]

\[
\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{3}
\]

where \( \alpha \) is the wave attenuation constant (Np/m) and \( \beta \) is the phase constant (rad/m).

For a general transmission line segment, the characteristic impedance \( Z_f \) and propagation constant \( \gamma \) are calculated as, respectively, as [11].

\[
Z_f = \frac{Z_{lf}}{Y_{cf}} = \frac{R_0 + (j\omega)\alpha c L_f}{G_0 + (j\omega)^2 C_f} \tag{6}
\]

\[
\gamma_f = \sqrt{(R_0 + (j\omega)\alpha c L_f)(G_0 + (j\omega)^2 C_f)} \tag{7}
\]

At high frequencies, the characteristic impedance, \( Z_f \) and propagation constant, \( \gamma_f \) can be evaluated using the following simplified expressions:

\[
Z_f = \sqrt{\frac{L_f}{C_f}} \omega^\frac{\alpha c - \alpha L_f}{2} \left[ \cos \left( \frac{\alpha_L - \alpha c}{2} \right) + \sin \left( \frac{\alpha_L - \alpha c}{2} \right) \right] \tag{8}
\]

\[
\gamma_f = \sqrt{\frac{L_f}{C_f}} \omega^\frac{\alpha c + \alpha L_f}{2} \left[ \cos \left( \frac{\alpha_L + \alpha c}{2} \right) + \sin \left( \frac{\alpha_L + \alpha c}{2} \right) \right] \tag{9}
\]

II. 3 Extraction of Transmission Line Parameters Using S-Parameters

In order to extract the per-unit parameters of the RLG C model from the measurements, the measured S-parameters of the transmission line are first converted to the ABCD matrix parameters. For this purpose, we use the inverse of the following relationship between two-port S-parameters and the ABCD matrix [10]

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix} = \begin{bmatrix}
A + B/Z_0 - CZ_0 - D & 2(AD - BC) \\
A + B/Z_0 + CZ_0 + D & -A + B/Z_0 + CZ_0 + D
\end{bmatrix} \tag{10}
\]

On the other hand, the ABCD matrix for a uniform transmission line with length \( l \) can be calculated in terms of the the characteristic impedance and the propagation constant as follows [12]:

\[
ABCD = \begin{bmatrix}
\cosh(\gamma l) & Z_0 \cdot \sinh(\gamma l) \\
\sinh(\gamma l)/2\alpha & \cosh(\gamma l)
\end{bmatrix} \tag{11}
\]

Given these basic relationships, we can now develop the procedure defined in Table I in order to retrieve the parameters of the transmission line model. Note that this
parameters of the classical model are obtained from Eqn. 10.

\[ \gamma = \alpha + j\beta = \frac{\sinh^{-1} \sqrt{BC}}{l} \]  

and \( Z_0 \) is, in turn, computed from the complex propagation constant using the following equation:

\[ Z_0 = \frac{\gamma}{(G + j\omega C)} \]  

where \( G = \omega C \text{tan} \delta \).

Finally, the RLGC parameters can be extracted from measurements using the followings equations:

\[ R = \text{Re}(\gamma/Z_0), \quad L = \text{Re}(\gamma Z_0)/\omega, \quad C = \text{Im}(\gamma/Z_0)/\omega, \quad \text{and} \quad G = \text{Re}(\gamma/Z_0). \]

**III. EXTRACTION OF THE TRANSMISSION LINE PARAMETERS**

In order to evaluate usefulness of the fractional order model, we have fabricated a microstrip line structure. The microstrip line geometries with FR-4 substrates are illustrated in Fig. 2.

For the microstrip line, the dimensions are set to \( l=25 \) mm; \( w=2 \) mm; \( h=1.0 \) mm; and \( t=0.035 \) mm. This transmission line is simulated in a high-frequency structure simulator (HFSS) and is optimized for the frequency range from 1 GHz to 16 GHz.

![Cross-section of the microstrip structure with FR-4 substrate.](http://www.bajece.com)

**TABLE I**

<table>
<thead>
<tr>
<th>S-parameters ( S_{11}, S_{21} )</th>
<th>Procedure for the Extraction of the Fractional-Order Transmission Line Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured using vector network analyzer.</td>
<td>ABCD parameters, ( y ), and ( Z_0 ) are obtained from Eqn. 10.</td>
</tr>
<tr>
<td>Using ( y ) and ( Z_0 ), RLCG parameter are derived (Eqn. 14).</td>
<td>( R_0, R_s, G_0, G_d ) parameters of the classical model are extracted from the respective characteristics using curve fitting (Eqn. 3).</td>
</tr>
<tr>
<td>Derivation of the main S-parameters ( S_{11}, S_{21} ) from the fractional order model (Using Eqns. 8&amp;9 in Eqn. 11)</td>
<td>( \alpha, \beta, L_0, C_f ) parameters of the fractional-order model are extracted from ( Z_0 ) and ( y ) using curve fitting (Eqns. 8&amp;9).</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_0 )</td>
<td>0.16</td>
<td>( \Omega/m )</td>
</tr>
<tr>
<td>( R_s )</td>
<td>3.47</td>
<td>m( \Omega/m\cdot Hz )</td>
</tr>
<tr>
<td>( L_0 )</td>
<td>302.49</td>
<td>nH/m</td>
</tr>
<tr>
<td>( C_0 )</td>
<td>0.118</td>
<td>F/m</td>
</tr>
<tr>
<td>( G )</td>
<td>0.017</td>
<td>S/m</td>
</tr>
<tr>
<td>( G_d )</td>
<td>2.37</td>
<td>Ps/m\cdot Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_0 )</td>
<td>1</td>
<td>( \Omega/m )</td>
</tr>
<tr>
<td>( L_f )</td>
<td>355</td>
<td>(nV( s^{-1} ))/A/m</td>
</tr>
<tr>
<td>( C_f )</td>
<td>4.62</td>
<td>(nAs( s^{-1} ))/V/m</td>
</tr>
<tr>
<td>( G )</td>
<td>0.017</td>
<td>S/m</td>
</tr>
<tr>
<td>( \alpha_0, \alpha_c )</td>
<td>0.834, 0.79</td>
<td>-</td>
</tr>
</tbody>
</table>

The per-unit-parameters of both integer and fractional-order models are derived from the experimental measurements using the procedure described in Table I. The values of the parameters thus obtained are given in Table II. Since the model equations are highly nonlinear, the optimization problem has many local minima, thus the parameters given in Table II should be considered as near optimum values.

The evaluations of the model accuracies are performed based on the characteristic impedance, \( Z_0 \) and the s-parameter, \( S_{21} \). The experimental results, the simulated characteristics using the integer and fractional order models are all given in Figs. 3 & 4. Experimental results and the characteristics obtained from the model for the characteristic impedance, \( Z_0 \) are given in Fig. 3(a), while the results related to the magnitude and phase functions of the \( S_{21} \) are given,

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respectively, in Figs. 3(b) and (c). The integer-order and fractional-order model parameters are the optimum parameters given in Table II.

As can be seen from the results in Fig. 3(b), both integer and fractional-order models give similar results for the phase characteristic of $S_{21}$. However, the accuracies of the models differ significantly for the characteristic impedance, $Z_0$ (see Fig. 3a) and the magnitude of the $s$-parameter, $|S_{21}|$ in Fig. 3c. Therefore, in Figs. 4(a) and (b), we have also provided the variations of the error function for the characteristic impedance, $Z_0$ and $|S_{21}|$, respectively.

From these characteristics, it is seen that fractional-order model approximates the experimental results more accurately in a wider-frequency range compared to the integer-order model. This advantage is more striking when the errors in the magnitude of the $S_{21}$ are considered.

IV. CONCLUSION

In this paper, the fractional-order model of the transmission line for the microstrip with FR-4 substrate is developed. This model is extracted via the measurements of the $S$-parameters. It is observed that fractional-order model allows more compact and accurate analytical model over wide-frequency band compared to the traditional integer order model. We have concluded that fractional-order characterization allows the derivation of an efficient model which incorporates the loss of the transmission line over a wide frequency range, thus is useful in applications requiring wide bandwidth. The results approximations of the (a) Magnitude of the characteristic impedance, $Z_0$ (b) Phase of $S_{21}$ in degrees, (c) Magnitude of $S_{21}$ in dB.

Fig. 4. Error variations of both integer-order and fractional-order RLGC models, (a) for the characteristic impedance, $Z_0$ (b) for the magnitude of $S_{21}$.
may be useful for those who design circuits for 5G technology built around high loss but low cost PCB materials.

REFERENCES


BIOGRAPHIES

OMER AYDIN has received his B.Sc. and M.Sc. in Electronics Engineering from Istanbul Technical University in 1982, 1985, respectively. He has completed his PhD on 4G and 5G radio power frequency amplifiers in 2016 in Istanbul Technical University (ITU). He is now working as a leader of Defence Technologies R&D, Netas Telecom. He has more than 20 scientific papers on 5G communication systems. His research interests include 5G communication systems, theoretical and practical aspects of radio frequency power amplifier designs.

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