Final Year Project Status Report:

Modelling Transmission line suitable for THz frequencies

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**Project Problem Description**

The development of efficient models for terahertz (THz) transmission lines is a critical challenge in modern telecommunications. THz frequencies, which range from 0.1 to 10 THz, offer exceptional bandwidth for applications such as high-speed wireless communication, imaging systems, and advanced sensing technologies. However, designing accurate and computationally efficient models for such systems is difficult due to the unique electromagnetic propagation characteristics at these frequencies, including high attenuation, significant dispersion, and nonlinearities.

A key problem lies in balancing computational efficiency and accuracy in modelling transmission line behaviour. Traditional methods, such as the finite-difference time-domain (FDTD) approach, often require significant computational resources and may not provide the desired level of precision in the time domain. Numerical methods like the Numerical Inverse Laplace Transform (NILT) and RLC ladder approximations offer alternative approaches but come with their own limitations, such as sensitivity to input parameters and numerical stability issues.

**Project Introduction**

**Area and Scope**

This project focuses on the numerical modelling of THz transmission lines using advanced computational methods. The scope includes implementing and validating models such as NILT and RLC ladder approximations to simulate time-domain behaviour accurately. The project also incorporates comparisons with other numerical solvers such as ODE45 to ensure robustness and efficiency in model development.

**Motivation**

The motivation for this work stems from the growing demand for high-speed communication systems operating at THz frequencies. These systems are vital for 6G networks, wireless data centres, and emerging applications like biomedical imaging. Accurate transmission line models are essential to enable the design and analysis of efficient systems for these use cases.

**Aim and Objectives**

* **Aim:** Develop and validate numerical models for THz transmission lines suitable for time-domain simulations.
* **Objectives:**
  + Use FDTD methods to create an initial approximation of the transmission line behaviour.
  + Understand and implement NILT to solve exact solutions in the s-domain.
  + Model the transmission line using RLC ladder approximations, convert them to impedances in the s-domain, and use NILT to compare these solutions with the exact solution to determine the number of sections required for accuracy without adding unnecessary complexity.
  + Derive a time-domain equivalent to simulate the RLC ladder and ultimately the transmission line.
  + Extend the models to simulate transmission line behaviour at various frequencies in the THz range.

**Critical Review of Background Theory and Literature**

**Review of THz Transmission Lines**

Terahertz (THz) transmission lines play a crucial role in high-speed communication, imaging, and sensing systems. However, accurately modelling their behaviour presents challenges due to unique propagation characteristics, such as high attenuation and dispersion. A fractional-order RLGC model for CMOS-based THz circuits, introduced by Shang et al. [4], incorporates causality and frequency-dependent losses, enabling precise analysis of THz transmission lines. Advanced designs, including cyclic olefin copolymer (COC)-based transmission lines, have also been proposed to minimize losses and enhance performance [1].

**Review of FDTD and RLC Ladder Approximations**

The finite-difference time-domain (FDTD) method is a widely known numerical technique for modeling transmission lines. Veerlavenkaiah and Raghavan [2] demonstrated how FDTD can calculate propagation constants effectively using MATLAB, offering a rigorous approach to simulating electromagnetic wave behaviour. Montoya [3] extended the use of FDTD to model transmission lines terminated with RLC loads, demonstrating its flexibility in handling practical termination scenarios. Brancik [7] explored time-domain simulations of multiconductor transmission line systems, emphasising the importance of accurate numerical methods for voltage and current wave propagation. While FDTD is robust and accurate, it is computationally demanding for large-scale or high-frequency systems.

The RLC ladder approximation provides a computationally efficient alternative by discretizing the transmission line into sections represented by lumped elements. However, this method can suffer from reduced accuracy at higher frequencies when insufficient sections are used. Paul [5] addressed this limitation by incorporating terminal constraints into RLC ladder approximations, improving their accuracy and reliability in FDTD analyses.

**Review of NILT for Time-Domain Analysis**

The Numerical Inverse Laplace Transform (NILT) offers a reliable means to approximate time-domain solutions from s-domain representations. Gad et al. [6] introduced an interpolation-supported NILT method that achieves fast and stable circuit simulations, making it a practical tool for analysing THz transmission lines. This project applies NILT to validate time-domain solutions obtained from FDTD and RLC ladder models. The versatility of NILT in MATLAB-based engineering simulations has been highlighted in prior work by Perutka [8], demonstrating its relevance for applications in electrical engineering and control systems.

**Comparison and Challenges**

Each reviewed method has distinct advantages and limitations. FDTD provides high accuracy but is resource-intensive, especially for long transmission lines or THz frequencies. RLC ladder approximations offer computational efficiency but require careful calibration to balance accuracy and complexity. NILT serves as a valuable tool for transforming exact s-domain solutions into the time domain, enabling validation of results from other methods. Challenges include ensuring numerical stability in NILT and optimizing the number of sections in RLC ladder models for THz applications.

**Proposed Solutions**

**How the Problem Will Be Addressed**The project proposes a step-by-step approach to model and simulate THz transmission lines:

1. **FDTD Approximation:**
   * Use the FDTD method to model the transmission line and obtain an initial time-domain approximation. This step will help understand the general behaviour of the system and validate subsequent methods.
2. **Understanding and Implementing NILT:**
   * **Study the NILT approach to solve the exact solution of the transmission line in the s-domain. NILT will be used to transform the exact s-domain solution into the time domain.**
3. **RLC Ladder Approximation:**
   * **Model the transmission line using an RLC ladder network, convert its components to impedances in the s-domain, and solve using NILT. Compare the results to the exact solution to determine the number of sections needed for accuracy while keeping the model computationally efficient.**
4. **Deriving a Time-Domain Equivalent:**
   * **From the validated RLC ladder approximation, derive a time-domain equivalent to simulate the transmission line directly. This step simplifies future analyses and reduces reliance on complex s-domain transformations.**
5. **Simulating Different Frequencies:**
   * **Extend the models to simulate the behavior of the transmission line at varying THz frequencies. Analyze the impact of frequency on accuracy, losses, and computational requirements.**

**Challenges and Mitigation:**

* **Numerical Stability: Fine-tune approximation parameters (e.g., step size h) in NILT and RLC ladder simulations.**
* **Complexity: Minimize computational overhead by optimizing the number of sections in the RLC ladder model.**

**Project Plan for Semester 2**

**References:**

1. A. Chahadih *et al*., "Low loss microstrip transmission-lines using cyclic olefin copolymer COC-substrate for sub-THz and THz applications," *2013 38th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, Mainz, Germany, 2013, pp. 1-2, doi: 10.1109/IRMMW-THz.2013.6665702.
2. D. Veerlavenkaiah and S. Raghavan, "Determination of propagation constant using 1D-FDTD with MATLAB," *2016 International Conference on Communication Systems and Networks (ComNet)*, Thiruvananthapuram, India, 2016, pp. 61-64, doi: 10.1109/CSN.2016.7823987.
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6. E. Gad, Y. Tao and M. Nakhla, "Fast and Stable Circuit Simulation via Interpolation- Supported Numerical Inversion of the Laplace Transform," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 12, no. 1, pp. 121-130, Jan. 2022, doi: 10.1109/TCPMT.2021.3122840.
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8. K. Perutka, Ed., *MATLAB for Engineers: Applications in Control, Electrical Engineering, IT and Robotics*. Rijeka, Croatia: InTech, 2011. Available: <https://doi.org/10.5772/2468>.
9. W. T. Smith and S. K. Das, "Application of asymptotic waveform evaluation for EMC analysis of electrical interconnects," *Proceedings of International Symposium on Electromagnetic Compatibility*, Atlanta, GA, USA, 1995, pp. 429-434, doi: 10.1109/ISEMC.1995.523595.

**1. Pozar, D. M. (2011). Microwave Engineering. John Wiley & Sons.**

You should prepare a **status report** (minimum three pages & maximum ﬁve pages) and submit it using this Loop site before 10.00 am on Monday 20th January.

* The main body of the document is **limited to five typed pages when you ignore inclusions such as Tables and Figures and your reference list**.
* In addition to the main body, you should have a title page, table of contents, list of figures and list of tables.
* You may have an appendix.
* A declaration page is not required as you are required to accept a declaration of originality when you upload your report to Loop.

The **Status Report** should include:

* A description of the project problem (**What** is the problem?  **Why** is there a problem?)
  + Introduce your project to the reader (what is the area, scope, motivation, aim & objective of your project? etc.)
  + Involves a critical review of the relevant background theory, practice and literature for problem.
* A description of any proposed solutions (**How** will the problem be addressed?)
  + A critical review of the relevant background theory, practice and literature for possible solutions.
* A list of at least **10** references, in the correct format that have been used in the two descriptive sections above.
  + These references must be of good 'academic' quality, i.e. from textbooks, peer-reviewed journals, conference papers, technical papers and publications, etc., and not from popular internet sources, e.g. Wikipedia.
  + The reference list should be provided at the end but should only contain references you have cited in the document.
* A project plan/schedule for Semester 2 with a maximum time unit of 1 week (**When** will the problem be addressed?)
  + The plan should include activities, tasks, deliverables and milestones, with identified issues to be addressed in the overall project development.

This **Status Report** will be marked under the following categories:

* Problem & Boundaries
* Alternative approaches/designs/solutions
* Background theory & referencing
* Project plan