

**DUBLIN CITY UNIVERSITY**

**SCHOOL OF ELECTRONIC ENGINEERING**

A Final Project report in

Simulation and exploration of THz TRNASMISSION LINES

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BACHELOR OF ENGINEERING

IN

ELECTRONIC AND COMPUTER ENGINEERING

MAJORING IN

THE INTERNET OF THINGS

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# Acknowledgements

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# Abstract

This final report presents the simulation and exploration of terahertz (THz) transmission lines, focusing on the development and validation of numerical models for high-frequency applications. The project addresses the challenges of accurately modelling THz transmission lines, which are essential for next-generation technologies such as 6G networks, wireless data centres, and biomedical imaging. The primary goal is to create computationally efficient and precise models capable of simulating time-domain behaviour at THz frequencies. Three key methods were employed: the Finite-Difference Time-Domain (FDTD) approach for initial approximations, the Numerical Inverse Laplace Transform (NILT) for exact s-domain solutions, and RLC ladder approximations for efficient time-domain modelling. The FDTD simulations provided a baseline for understanding transient and steady-state behaviours, while the RLC ladder method, combined with NILT, demonstrated the ability to closely match exact solutions when sufficient sections were used. Additionally, Y-parameters were derived to analyse transmission line behaviour, and Asymptotic Waveform Evaluation (AWE) was implemented to refine approximations and extract dominant system responses. The final model was obtained through iterative addition of small responses at high frequencies and comparison with exact solutions. The results highlight the importance of optimising the number of sections in the model to balance accuracy and computational efficiency. This work contributes to the advancement of THz communication systems by providing reliable modelling tools for future research and development.

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[**Figure 1.1**. A Nice Picture. **Error! Bookmark not defined.**](#_Toc381621110)

[**Figure 2.1** A Sample Figure **Error! Bookmark not defined.**](#_Toc381621111)

# Chapter 1 - Introduction

The growth of communication technologies has led to the exploration of terahertz (THz) frequencies (0.1 to 10 THz) for applications like 6G networks, wireless data centres, and biomedical imaging, but accurate THz transmission line models remain a challenge. The motivation comes from the demand for high-speed THz communication systems, which are crucial for future technologies, but currently lack reliable and efficient modelling tools.

This project aims to develop and validate efficient numerical models for THz transmission lines to predict signal behaviour and optimize system performance. The study addresses key propagation challenges at THz frequencies, such as high attenuation and dispersion, which are critical for the design of next-generation communication systems. To achieve this, the project evaluates original methods and techniques proposed between 2000 and 2010, assessing their suitability for THz applications. In addition, the research focuses on developing an accurate model using Y-parameters and Asymptotic Waveform Evaluation (AWE). The developed model is then compared with the original methods to determine their effectiveness and limitations at THz frequencies

Three primary methods are employed in this study: Finite-Difference Time-Domain (FDTD) for transient analysis, Numerical Inverse Laplace Transform (NILT) for exact s-domain solution, and RLC ladder approximations for computational efficiency. The FDTD method provides a foundation for simulating time-domain electromagnetic wave propagation, while NILT offers precise frequency-domain insights. The RLC ladder approximations, on the other hand, are used to simplify complex transmission line models, making them computationally tractable for large-scale simulations. These methods are compared against each other and the obtained model using Y-parameters and Asymptotic Waveform Evaluation (AWE) to evaluate their effectiveness for THz applications. Factors affecting their performance, such as the number of sections, computational cost, and accuracy, are analysed to determine the most efficient approach for THz transmission line modelling.

The report includes a literature review, implementation details of these modelling methods, simulation results, challenges faced, and future work plans. By integrating Y-parameters and AWE into the modelling framework, this research aims to establish a validated numerical approach for THz transmission line modelling.  The proposed model not only addresses the limitations of earlier methods but also offers a computationally efficient and accurate solution for THz signal analysis. By comparing the developed model with original methods from 2000 to 2010, this study provides valuable insights into the evolution of THz modelling techniques and their applicability to modern communication systems. This research aims to advance THz communication technologies by designing high-performance systems capable of operating at extreme frequencies.

### 1.2.4 Summary

This project develops and validates numerical models for THz transmission lines to optimize system performance and address propagation challenges. Three primary methods—FDTD, NILT (exact solution), and RLC ladder approximations—are evaluated for accuracy, computational efficiency, and effectiveness compared to the obtained model using AWE. MATLAB is used for implementation, but these methods can be applied using any coding language or software.

# - Technical Background

Modelling THz (0.1–10 THz) transmission lines require understanding wave propagation, transmission line theory, and numerical methods. At THz frequencies, the behaviour of transmission lines is governed by the Telegrapher's equations (1), which describe the relationship between voltage and current along the line. These equations are derived from Maxwell's equations and are given by:

(1)

where and  represent the voltage and current at position  and time , respectively. and *C* are the per-unit-length resistance, inductance, conductance, and capacitance of the transmission line. At THz frequencies, these parameters become highly frequency-dependent, making accurate modelling more complex.

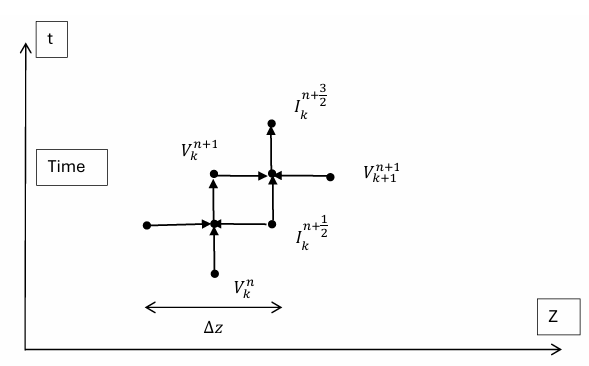
**Finite-Difference Time-Domain (FDTD) Method**

The FDTD method is a widely used numerical technique for solving electromagnetic problems, particularly in the time domain. It discretizes the transmission line into small segments as in Figure 1, allowing for the simulation of voltage and current over time. The FDTD method is based on approximating the derivatives in the Telegrapher's equations using finite differences [3][5]. In this approach voltages (​) are calculated at the ends of each section, while currents (​​) are computed at the middle of each section as illustrated in Figure 1 and 2. Then, ​ and ​​​ can be derived as.

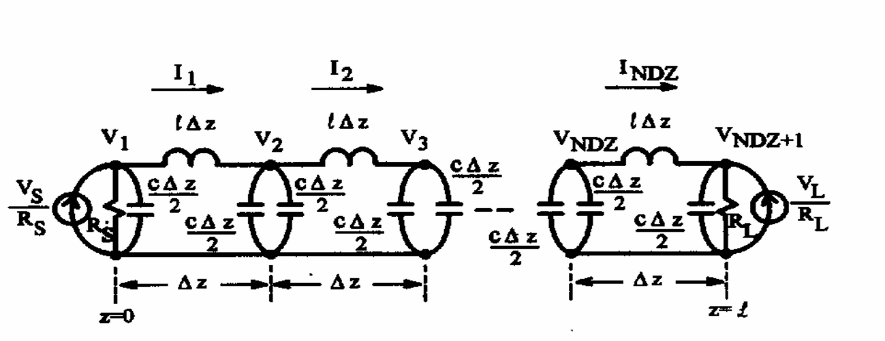
(3)

(2)

This method provides a foundation for simulating transient and steady-state behaviors of transmission lines, but it can be computationally intensive, especially for long lines or high frequencies.



**Figure 2:** Staggered grid representation for the FDTD method, illustrating the spatial (z) and temporal (t) discretization. The voltage (V) is defined at grid points, while the current (I) is defined at the midpoints between the grid points [5].



**Figure 1:** Equivalent representation of the transmission line using the Lumped Pi circuit model, illustrating the discretization of inductance and capacitance along the line [5].

**Numerical Inverse Laplace Transform (NILT)**

The NILT method is a powerful tool for convert frequency-domain solutions into time-domain solutions for simulating transient phenomena in multiconductor transmission line (MTL) systems [6]. It is based on the Bromwich integral, which is numerically evaluated using the Fast Fourier Transform (FFT) and the quotient-difference (q-d) algorithm. The time-domain function *f*(*t*) is approximated using a discrete form derived from the Laplace transform *F*(*s*) as in 4. The approximation involves a finite sum evaluated by the FFT and an infinite sum accelerated by the q-d algorithm, which uses a continued fraction to improve convergence.

(4)

This approach allows for the exact solution of the transmission line's behaviour in the s-domain, which can then be compared with approximate methods such as the RLC ladder to validate accuracy.

**RLC Ladder Approximations**

The RLC ladder method approximates a transmission line by dividing it into multiple sections, each represented by lumped resistive (R), inductive (L), and capacitive (C) elements as shown in Figure 3. This discretization simplifies the transmission line into a network of interconnected RLC circuits, making it easier to model and simulate

A diagram of a circuit

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**Figure 3:** RLC ladder network approximates a transmission line with N sections and lumped elements (R), (L), and (C).

Governing equations:

Considering one section of the RLC ladder, the following equations are derived:

(6)

(5)

Here, represents the length of a small segment of the transmission line and is defined as:

(7)

where *l* is the total length of the line, and N*N* is the number of sections or RLC circuits used to model the line.

(8)

(9)

(10)

(11)

The impedances *R*, *L*, and *C* are defined per unit length (i.e., per *dz*) in Equations (5) and (6). By rearranging Equations (5) and (6), Equations (8) and (9) are obtained. For the *n*-th section, the generalised forms are given by Equations (10) and (11). The accuracy of the RLC ladder approximation depends on the number of sections used; more sections generally lead to higher accuracy but at the cost of increased computational complexity. The RLC ladder method is particularly useful for simulating long transmission lines or systems with complex terminations.

**Asymptotic Waveform Evaluation (AWE):**

**Y-parameters:**

## 2.2 Summary

# - Design of …

1. The FDTD method is a widely used numerical technique for solving electromagnetic

a multiconductor line?

1. RLC ladder
2. Explain it as, how can we plot it, why is it better than FDTD.
3. Exact solution:

A diagram of a parallel diagram

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1. NILT0 and how it works? Why we need it?

Challenges?

NILTcv:

A black and white triangle with small black letters

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1. AWE..what is it and why?

AWE involves 4 main steps:

1. Form a state – space representation

2. Form the moments

3. Find the poles of the system

4. Find the residues

And then form the impulse response as:

1. Recursive convolution based on the pole-residue representation
2. Generalise converting the RLC ladder to state space with N number of section?
3. Y parameters:
4. Compare acquired model with the exact model at different frequencies and validate it.(next few weeks )

# Chapter 4- Implementation and Testing of …

Provide a detailed explanation of all completed code implementations, including their testing processes, challenges encountered, and associated limitations. Additionally, include example tests for each point or method mentioned above.

1. PSPICE Simulation?

# Chapter 5 - Results and Discussion

Analyse all figures and results corresponding to specific values, explaining their significance and whether they align with expectations. Discuss any discrepancies, potential sources of error, and the reasoning behind why the results may or may not be valid.

1. Complex frequency hopping?

# Chapter 6 – Ethics

# Chapter 7 - Conclusions and Further Research

# 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.
3. T. P. Montoya, "Modeling 1-D FDTD transmission line voltage sources and terminations with parallel and series RLC loads," *IEEE Antennas and Propagation Society International Symposium (IEEE Cat. No.02CH37313)*, San Antonio, TX, USA, 2002, pp. 242-245 vol.4, doi: 10.1109/APS.2002.1016969.
4. Y. Shang, H. Yu and W. Fei, "Design and Analysis of CMOS-Based Terahertz Integrated Circuits by Causal Fractional-Order RLGC Transmission Line Model," in *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 3, no. 3, pp. 355-366, Sept. 2013, doi: 10.1109/JETCAS.2013.2268948.
5. C. R. Paul, "Incorporation of terminal constraints in the FDTD analysis of transmission lines," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 36, no. 2, pp. 85-91, May 1994, doi: 10.1109/15.293284.
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.
7. L. Brancik, "Matlab based time-domain simulation of multiconductor transmission line systems," *The IEEE Region 8 EUROCON 2003. Computer as a Tool.*, Ljubljana, Slovenia, 2003, pp. 464-468 vol.1, doi: 10.1109/EURCON.2003.1248066.
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.
10. F. Vandrevala, "Transmission Line Model for Material Characterization using Terahertz Time-Domain Spectroscopy," Ph.D. dissertation, Univ. of Virginia, July 2019.

# Appendix 1