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Brayan Alexander
Munoz Barrera

Desenvolvimento de Algoritmo de Simulação Modular para diferentes ambientes

Development of a Modular Simulation Algorithm for Different Environments

DOCUMENTO PROVISÓRIO

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Desenvolvimento de Algoritmo de Simulação Modular para diferentes ambientes

Development of a Modular Simulation Algorithm for Different Environments

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em MASTER DEGREE IN MATHEMATICS AND APPLICATIONS, realizada sob a orientação científica do Doutor (nome do orientador), Professor associado do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro, do Doutor (co-orientador), Professor auxiliar convidado do Departamento de Matemática da Universidade de Aveiro, da Doutora (co-orientadora), Professora associada c/ agregação do Departamento de Biologia da Universidade de Aveiro, e do Doutor (co-orientador), Professor auxiliar convidado do Departamento de Física da Universidade de Aveiro.

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Prof. Doutor João Antunes da Silva
professor associado da Universidade de Aveiro

vogais / examiners committee

Prof. Doutor João Antunes da Silva
professor associado da Universidade de Aveiro

Prof. Doutor João Antunes da Silva
professor associado da Universidade de Aveiro

Prof. Doutor João Antunes da Silva
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professor associado da Universidade de Aveiro

Prof. Doutor João Antunes da Silva
professor associado da Universidade de Aveiro

agradecimentos / **acknowledgements**

Agradecimientos a mis cuchos y mi gata.

palavras-chave texto livro, arquitetura, história, construção, materiais de construção, saber tradicional.

resumo Um resumo é um pequeno apanhado de um trabalho mais longo (como uma tese, dissertação ou trabalho de pesquisa). O resumo relata de forma concisa os objetivos e resultados da sua pesquisa, para que os leitores saibam exatamente o que se aborda no seu documento.
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Uma maneira comum de estruturar um resumo é usar a estrutura IMRaD. Isso significa:

- Introdução
- Métodos
- Resultados
- Discussão

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keywords

textbook, architecture, history, construction, construction materials, traditional knowledge.

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An abstract is a short summary of a longer work (such as a thesis, dissertation or research paper).
The abstract concisely reports the aims and outcomes of your research, so that readers know exactly what your paper is about.
Although the structure may vary slightly depending on your discipline, your abstract should describe the purpose of your work, the methods you've used, and the conclusions you've drawn.
One common way to structure your abstract is to use the IMRaD structure. This stands for:

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acknowledgement of use of AI tools

Recognition of the use of generative Artificial Intelligence technologies and tools, software and other support tools.

I acknowledge the use of [insert AI system(s) and link] to [specific use of generative artificial intelligence or other tasks]. I acknowledge the use of [software, codes or platforms] to [specific use software, codes or platforms or to other tasks].

Example 1: I acknowledge the use of ChatGPT 3.5 (Open AI, https://chat.openai.com) to summarise the initial notes and to proofread the final draft and the use of Office365 (Microsoft, https://www.office.com) for text writing and productivity.

Example 2: No content generated by AI technologies has been used in this Thesis.

Contents

List of Figures

List of Tables

Glossário

CHAPTER 1

Introdução

A short description of the chapter.
A memorable quote can also be used.

1.1 Acrónimos

Primeira e seguintes referências: **h2o!** (**h2o!**), **h2o!**
Plural, acrónimo expandido e curto: **h2o!**s, **h2o!**, **h2o!**
Com citação[1]: **adsl!** (**adsl!**), **adsl!**

1.2 Fontes

- Tiny
- Scriptsize
- Footnotes
- Small
- Normal
- large
- Large
- LARGE
- huge
- Huge

1.3 Unidades

Utilizando o pacote `siunitx` é possível utilizar unidades do Sistema Internacional. Exemplo: a aceleração da gravidade é de $9.8\,\mathrm{m\,s^{-2}}$ e um ficheiro ocupa 1 MiB.

[1]Necessária entrada na bibliografia

1.4 Code Blocks

Uma listagem pode ser apresentada com o ambiente `listing`, que é um float (objeto flutuante, tal como uma figura ou uma tabela).

A listagem em Código **??** mostra um exemplo em C.

```c
#include <stdio.h>
#define N 10
/* Block
 * comment */

int main()
{
    int i;

    // Line comment.
    puts("Hello world!");

    for (i = 0; i < N; i++)
    {
        puts("LaTeX is also great for programmers!");
    }

    return 0;
}
```

Código 1: This caption appears below the code.

1.5 Citações

Algumas formas distintas de citar:

- **Apenas referência**: **rfc44**
- **Apenas data**: **rfc44**
- **Apenas ano**: **rfc44**
- **Apenas autor**: **rfc44**
- **Apenas editor:rfc44**
- **Autor e referência:rfc44**

CHAPTER 2

State of the Art

This chapter presents a literature review and state of the art related to the theme of this dissertation. The most relevant works and existing technologies in the area are analyzed, focusing on simulation platforms for energy systems, mobility networks, telecommunications, and co-simulation frameworks.

2.1 Introduction

This chapter provides a comprehensive overview of existing simulation tools and frameworks across multiple domains that are relevant to this work. The review is organized by domain: energy systems simulation, mobility and traffic simulation, telecommunications network simulation, and co-simulation frameworks that enable integration across these domains.

2.2 Context and Theoretical Foundations

2.2.1 Domain-Specific Simulation

2.2.2 Co-Simulation Paradigms

2.3 Energy Systems Simulation

Energy system simulation tools are essential for analyzing power grid behavior, renewable energy integration, and smart grid operations. This section reviews the main platforms used for energy system modeling and analysis.

2.3.1 SimCES Platform

The SimCES platform **simces** provides a modular simulation framework featuring platform independence, container ecosystem, and a comprehensive development toolkit. This platform enables flexible and scalable simulation of complex energy systems through its containerized architecture, allowing researchers to develop and deploy simulation components in isolated environments.

2.3.2 PyPSA: Python for Power System Analysis

PyPSA **pypsa** is an open-source toolbox for simulating and optimizing modern power systems. Written in Python, it provides a user-friendly interface for power flow analysis, optimal power flow calculations, and energy system optimization. PyPSA supports modeling of conventional and renewable generation, storage systems, and sector coupling.

2.3.3 GridLAB-D

GridLAB-D **gridlabd** is an agent-based simulation framework specifically designed for smart grid analysis. It enables detailed modeling of distribution systems, including residential loads, distributed generation, and smart grid technologies. The agent-based approach allows for realistic representation of individual components and their interactions within the power distribution network.

2.3.4 Pandapower

Pandapower **pandapower** is an open-source power system analysis and optimization tool written in Python. It combines the data analysis capabilities of pandas with the performance of PYPOWER to provide an easy-to-use yet powerful tool for power system analysis. Pandapower supports steady-state network analysis, optimal power flow, and includes extensive libraries of network elements, making it particularly suitable for distribution network studies and integration with data analytics workflows.

2.3.5 OpenDSS

OpenDSS (Open Distribution System Simulator) **opendss** is a comprehensive electrical power system simulation tool developed by the Electric Power Research Institute (EPRI). It specializes in distribution system and distributed resource analysis, supporting harmonic analysis, dynamic simulations, and renewable energy integration studies. OpenDSS is widely used in industry and academia for analyzing the impact of distributed generation, energy storage, and electric vehicles on distribution networks.

2.4 Mobility and Traffic Simulation

Traffic and mobility simulation tools are crucial for analyzing transportation networks, optimizing traffic flow, and evaluating the impact of new mobility solutions on urban infrastructure.

2.4.1 Overview of Agent-Based Traffic Simulators

The work by **agent_traffic_overview** provides a comprehensive overview of agent-based traffic simulators, comparing different approaches and highlighting their respective strengths and limitations. Agent-based models allow for microscopic representation of individual vehicles and their decision-making processes.

2.4.2 SUMO Simulator and Extensions

The Simulation of Urban Mobility (SUMO) is one of the most widely used open-source traffic simulation platforms. Recent advances include the integration of machine learning approaches for realistic traffic generation.

Realistic Traffic Generation with Federated Learning

Recent research **sumo_federated** has introduced a realistic urban traffic generator using decentralized federated learning for the SUMO simulator. This approach enables generation of more realistic traffic patterns while preserving privacy through decentralized learning mechanisms.

2.4.3 MATSim

MATSim (Multi-Agent Transport Simulation) **matsim** is a large-scale agent-based transport simulation framework. It enables modeling of individual travelers' daily activity patterns and their interactions with transportation networks. MATSim is particularly suited for analyzing large metropolitan areas and evaluating transportation policies.

2.4.4 VISSIM

VISSIM **vissim** is a commercial microscopic multi-modal traffic flow simulation software developed by PTV Group. It enables detailed modeling of urban traffic, public transport operations, and pedestrian dynamics. VISSIM provides advanced vehicle behavior models, 3D visualization capabilities, and extensive data collection features, making it a popular choice for traffic engineering applications, impact studies, and infrastructure planning.

2.4.5 AIMSUN

AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) **aimsun** is a comprehensive traffic modeling software that supports microscopic, mesoscopic, and macroscopic simulation approaches. It enables integrated modeling of traffic management strategies, public transport operations, and connected and autonomous vehicles. AIMSUN is extensively used for smart mobility studies, real-time traffic management, and transportation planning.

2.5 Telecommunications Network Simulation

Telecommunications simulation tools enable analysis of mobile networks, protocol performance, and network behavior under various conditions.

2.5.1 SiMoNe: Simulator for Mobile Networks

SiMoNe **simone**, **simone_icc** is a system-level simulator for mobile networks that enables realistic scenario modeling. It provides capabilities for simulating mobile network behavior in the context of realistic user mobility patterns and traffic demands. SiMoNe supports evaluation of network performance, resource allocation strategies, and quality of service metrics.

2.5.2 ns-3 Network Simulator

ns-3 **ns3** is a discrete-event network simulator widely used in research and education. It provides detailed protocol implementations and supports simulation of various network types, including wireless sensor networks, cellular networks, and Internet protocols. ns-3 offers high fidelity in protocol modeling and is extensively validated against real-world measurements.

2.5.3 OMNeT++

OMNeT++ **omnetpp** is a component-based, modular simulation framework primarily used for network simulation. Its modular architecture and extensive library of protocol models (INET Framework) make it suitable for telecommunications research. OMNeT++ supports both wired and wireless network simulation with detailed physical layer modeling.

2.5.4 Vienna 5G System Level Simulator

The Vienna 5G System Level Simulator **vienna5g** is an open-source MATLAB-based simulator for 5G mobile networks. It provides detailed modeling of 5G NR (New Radio) physical layer and system-level performance evaluation. The simulator supports various deployment scenarios, antenna configurations, and enables analysis of massive MIMO, beamforming, and network slicing capabilities. It is widely used in academia for 5G research and standardization activities.

2.5.5 Network Simulator 2 (ns-2)

Network Simulator 2 (ns-2) **ns2** is a discrete-event network simulator that has been extensively used in networking research for decades. While largely superseded by ns-3, ns-2 remains relevant due to its extensive protocol libraries and large body of validated models. It supports simulation of TCP, routing protocols, multicast protocols, and wireless networks, with a particular strength in ad-hoc network simulation.

2.6 Co-Simulation Frameworks

Co-simulation frameworks enable integration of multiple domain-specific simulators, allowing analysis of interdependencies and interactions across different systems.

2.6.1 HELICS Framework

The Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) **helics** is a co-simulation framework designed for scalable multi-domain modeling and analysis. HELICS enables integration of diverse simulators from different domains (energy, transportation, telecommunications) through a flexible message-passing architecture. It supports large-scale simulations with thousands of federates and provides mechanisms for time synchronization and data exchange between heterogeneous simulation tools.

HELICS was developed by the U.S. Department of Energy to address the need for analyzing interdependencies in large-scale infrastructure systems. The framework provides several key capabilities that make it particularly suitable for complex co-simulation scenarios:

Architecture and Components: HELICS employs a hierarchical broker-based architecture that enables efficient communication between simulation components (federates). The core components include:

- **Federates:** Individual simulation tools or components that participate in the co-simulation
- **Brokers:** Intermediaries that manage communication and time synchronization between federates
- **Core:** Communication layer that handles message routing and delivery

Time Management: HELICS implements sophisticated time synchronization algorithms that support both time-stepped and event-driven simulators. It provides conservative and optimistic time advancement strategies, ensuring causality is preserved across the co-simulation.

Data Exchange: The framework supports multiple communication paradigms including publish-subscribe, value-based interfaces, and message-based communication. This flexibility allows simulators with different data exchange requirements to be integrated seamlessly.

Scalability: HELICS has been demonstrated to scale to thousands of federates in distributed computing environments, making it suitable for analyzing city-scale or regional infrastructure systems.

Language Support: HELICS provides APIs for multiple programming languages including C++, Python, Java, MATLAB, and Julia, facilitating integration with a wide variety of existing simulation tools.

Platform Independence: The framework runs on Windows, Linux, and macOS, and supports both local and distributed co-simulation deployments.

2.6.2 Justification for HELICS Selection

For this work, HELICS was selected as the co-simulation framework based on the following criteria and comparative analysis:

Scalability Requirements: The need to potentially simulate large-scale scenarios involving thousands of interacting components (energy nodes, vehicles, communication devices) necessitates a framework with proven scalability. HELICS has been demonstrated to scale to city-level and regional infrastructure simulations, outperforming alternatives like Mosaik in distributed scenarios.

Multi-Domain Support: Unlike domain-specific frameworks (FMI for continuous systems, Mosaik for smart grids), HELICS is explicitly designed for heterogeneous multi-domain co-simulation, supporting the integration of energy, mobility, and telecommunications simulators required for this work.

Time Synchronization: HELICS provides sophisticated time management algorithms that handle both time-stepped simulators (common in energy and mobility domains) and event-driven simulators (typical in telecommunications). This flexibility is essential for maintaining causality and accuracy across domains with different temporal characteristics.

Active Development and Community: HELICS benefits from ongoing development supported by the U.S. Department of Energy and has an active user community. This ensures continued maintenance, bug fixes, and feature additions, as well as availability of support and documentation.

Language and Platform Support: The availability of APIs for Python, C++, Java, and MATLAB enables integration with the diverse set of simulation tools used in this work without extensive wrapper development. Platform independence ensures deployment flexibility.

Performance and Efficiency: HELICS's hierarchical broker architecture and optimized communication protocols provide better performance for large-scale distributed co-simulations compared to centralized approaches like Mosaik or agent-based frameworks like MECSYCO.

Industry and Research Adoption: HELICS is increasingly adopted in research and industry projects related to infrastructure co-simulation, providing a pathway for practical application and validation of the work presented in this dissertation.

Table **??** summarizes the comparison of co-simulation frameworks against key requirements for this work.

Table 2.1: Comparison of co-simulation frameworks

Framework	**Scalability**	**Multi-Domain**	**Time Sync**	**Language Support**	**Community**
HELICS	Excellent	Yes	Advanced	Multiple	Large
FMI/FMU	Moderate	Limited	Good	Standard	Very Large
Mosaik	Limited	Partial	Basic	Python-focused	Moderate
MECSYCO	Moderate	Yes	Moderate	Java-focused	Small
FNCS	Good	Yes	Good	Multiple	Deprecated

2.7 Comparative Analysis

This section compares the different simulation approaches and tools presented, highlighting their strengths, limitations, and applicability to different use cases.

2.7.1 Energy Simulators Comparison

Table 2.2: Comparison of energy system simulators

Tool	Strengths	Limitations	Primary Use
SimCES	Modular, containerized, platform-independent	Relatively new, limited community	Flexible energy system modeling
PyPSA	Python-based, easy to use, optimization focus	Limited real-time capabilities	Power system optimization
GridLAB-D	Agent-based, detailed distribution modeling	Steep learning curve	Smart grid analysis
Pandapower	Python integration, extensive libraries	Steady-state focus	Distribution network analysis
OpenDSS	Industry standard, comprehensive features	Complex for beginners	DER and distribution studies

2.7.2 Mobility Simulators Comparison

Table 2.3: Comparison of mobility and traffic simulators

Tool	Strengths	Limitations	Primary Use
SUMO	Open-source, widely used, extensible	Limited multi-modal support	Urban traffic simulation
MATSim	Large-scale, agent-based, activity modeling	High computational requirements	Metropolitan transport planning
VISSIM	3D visualization, detailed modeling	Commercial license required	Traffic engineering
AIMSUN	Multi-scale, real-time capable	High cost, steep learning curve	Smart mobility studies

2.7.3 Telecommunications Simulators Comparison

Table 2.4: Comparison of telecommunications simulators

Tool	Strengths	Limitations	Primary Use
SiMoNe	Realistic scenarios, system-level	Limited protocol detail	Mobile network planning
ns-3	High fidelity, validated protocols	Steep learning curve	Protocol research
OMNeT++	Modular, extensive libraries	Complex setup	Network protocol development
Vienna 5G	5G NR focus, MATLAB-based	Limited to 5G scenarios	5G research
ns-2	Extensive legacy protocols	Outdated architecture	Ad-hoc networks

2.7.4 Integration and Co-Simulation

The reviewed simulators excel in their respective domains but lack native support for cross-domain interaction. HELICS addresses this gap by providing a standardized framework for co-simulation, enabling researchers to couple multiple simulators and analyze system-wide interactions.

2.8 Research Gaps and Opportunities

Despite the availability of sophisticated simulation tools in each domain, several challenges remain:

- **Limited integration:** Most simulators operate in isolation, making it difficult to analyze cross-domain dependencies
- **Scalability:** Coupling multiple high-fidelity simulators presents computational challenges
- **Data exchange:** Standardized interfaces for data exchange between heterogeneous simulators are lacking
- **Synchronization:** Time synchronization across simulators with different time scales remains challenging
- **Validation:** Limited validation of co-simulation results against real-world measurements

2.9 Summary

This chapter reviewed the state of the art in simulation tools across energy, mobility, and telecommunications domains, as well as co-simulation frameworks. Each domain has mature simulation tools with specific strengths, but integration across domains remains an active research area.

The identified gaps motivate the work presented in this dissertation, which aims to address the challenges of multi-domain simulation integration through [describe your approach here].

The following chapter presents the methodology adopted to address these challenges and achieve the objectives of this work.

CHAPTER 3

Methodology

This chapter describes the methodology adopted to achieve the objectives of this dissertation. It presents the approach, methods, techniques, and tools used throughout the research and development process.

3.1 Introduction

3.2 Research Approach

3.3 System Architecture

figs/architecture.png

Figure 3.1: System architecture overview

3.3.1 Component A

3.3.2 Component B

3.4 Design Decisions

3.4.1 Technology Selection

3.4.2 Design Patterns and Best Practices

3.5 Development Process

3.6 Data Collection and Analysis

3.7 Evaluation Methodology

3.7.1 Performance Metrics

3.7.2 Simulation Scenarios

To validate the proposed co-simulation framework and evaluate its effectiveness in modeling cross-domain interactions, six distinct scenarios were designed covering energy systems, mobility networks, and telecommunications domains. Each scenario is designed to test specific aspects of the framework's capabilities and demonstrate realistic use cases.

Energy Domain Scenarios

Scenario E1: Smart Grid with Renewable Integration

This scenario simulates a distribution network with high penetration of renewable energy sources (solar and wind) and distributed energy storage systems. The scenario focuses on:

- Grid topology: IEEE 33-bus distribution system modified with 40% renewable penetration
- Time frame: 24-hour simulation with 15-minute time steps
- Key components:
  - 10 rooftop solar PV installations (2-5 kW each)
  - 2 wind turbines (100 kW each)
  - 5 battery energy storage systems (50 kWh each)
  - 800 residential loads with smart meters
- Objectives:
  - Analyze voltage profile stability under variable renewable generation
  - Evaluate energy storage dispatch strategies
  - Assess demand response effectiveness during peak hours
  - Quantify renewable energy curtailment
- Expected outputs: Voltage profiles, power flows, storage state-of-charge, renewable curtailment metrics

Scenario E2: Electric Vehicle Charging Infrastructure

This scenario models the impact of electric vehicle (EV) charging on the distribution network, with coordinated and uncoordinated charging strategies. The scenario includes:

- Grid topology: Modified IEEE 13-node test feeder with residential and commercial areas
- Time frame: 24-hour simulation with 5-minute time steps
- Key components:
  - 100 electric vehicles with varying arrival times and charging needs
  - 20 Level 2 charging stations (7.2 kW) in residential areas
  - 5 DC fast charging stations (50 kW) in commercial zones
  - Time-of-use tariff structure
- Objectives:
  - Compare uncoordinated vs. smart charging impacts on grid load
  - Analyze transformer loading and potential overload conditions
  - Evaluate vehicle-to-grid (V2G) potential for grid support
  - Assess economic benefits of different charging strategies
- Expected outputs: Load profiles, transformer loading, voltage deviations, charging costs, grid support metrics

Mobility Domain Scenarios

Scenario M1: Urban Traffic Congestion Management

This scenario simulates traffic flow in an urban area with intelligent traffic management systems and evaluates congestion mitigation strategies. The scenario comprises:

- Network topology: 5 km $\times$ 5 km urban grid with 25 signalized intersections
- Time frame: 3-hour morning peak period with 1-second simulation steps
- Key components:
  - 2,500 vehicles with varied origin-destination pairs
  - Adaptive traffic signal control system
  - 3 alternative routes for major corridors
  - Real-time traffic information system
- Objectives:
  - Evaluate adaptive signal timing effectiveness on travel times
  - Analyze traffic flow distribution across alternative routes
  - Assess congestion hotspot formation and dissipation
  - Quantify emissions reduction from optimized traffic flow
- Expected outputs: Average travel times, queue lengths, intersection delays, throughput, emissions

Scenario M2: Autonomous Vehicle Integration

This scenario examines the integration of connected autonomous vehicles (CAVs) in mixed traffic conditions, focusing on safety and efficiency improvements. The scenario features:

- Network topology: 10 km highway section with on/off ramps and urban arterial
- Time frame: 2-hour simulation with 0.5-second time steps
- Key components:
  - 1,000 total vehicles with varying CAV penetration rates (0%, 25%, 50%, 75%)
  - Vehicle-to-vehicle (V2V) communication (200m range)
  - Cooperative adaptive cruise control (CACC)
  - Lane change assistance systems
- Objectives:
  - Analyze highway capacity improvements with increasing CAV penetration
  - Evaluate safety metrics (time-to-collision, hard braking events)
  - Assess platooning effectiveness on fuel consumption
  - Compare human driver vs. autonomous vehicle behavior patterns
- Expected outputs: Capacity metrics, safety indicators, fuel consumption, platoon statistics

Telecommunications Domain Scenarios

Scenario T1: 5G Network Slicing for Smart City Services

This scenario simulates a 5G mobile network serving multiple smart city applications with different quality of service requirements through network slicing. The scenario includes:

- Network topology: Urban area (4 km^2) with 7 base stations (gNBs)
- Time frame: 1-hour simulation with dynamic user mobility
- Key components:
  - 500 user devices with varying mobility patterns
  - 3 network slices: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency (URLLC), massive Machine-Type Communications (mMTC)
  - Applications: video streaming (eMBB), autonomous vehicles (URLLC), smart meters (mMTC)
  - Heterogeneous network with macro and small cells
- Objectives:
  - Evaluate slice isolation and resource allocation efficiency
  - Analyze quality of service for different application types
  - Assess network capacity under varying load conditions
  - Measure handover performance for mobile users
- Expected outputs: Throughput per slice, latency distributions, packet loss rates, resource utilization

Scenario T2: IoT Network Performance Under High Density

This scenario evaluates telecommunications network performance in a dense IoT deployment typical of smart city or industrial environments. The scenario comprises:

- Network topology: Industrial park (2 km^2) with 4 LTE/5G base stations
- Time frame: 24-hour simulation with periodic and event-driven traffic
- Key components:
  - 5,000 IoT devices (sensors, actuators, smart meters)
  - NB-IoT and LTE-M connectivity
  - Periodic reporting (every 15 minutes) and alarm-based events
  - Edge computing nodes for data aggregation
- Objectives:
  - Analyze network congestion during synchronized reporting periods
  - Evaluate coverage and penetration loss effects on connectivity
  - Assess battery life implications of different transmission strategies
  - Measure edge computing offloading benefits
- Expected outputs: Connection success rates, latency statistics, energy consumption, coverage maps

Cross-Domain Integration Scenarios

In addition to the domain-specific scenarios, integrated cross-domain scenarios will be developed to validate the co-simulation framework's ability to capture interdependencies:

- **Integrated Scenario 1:** EV charging (Energy + Mobility) - Couples Scenario E2 with Scenario M1 to model EVs navigating to charging stations based on traffic conditions and station availability
- **Integrated Scenario 2:** Connected mobility (Mobility + Telecommunications) - Combines Scenario M2 with Scenario T1 to analyze how 5G network performance affects CAV operations
- **Integrated Scenario 3:** Smart grid with IoT monitoring (Energy + Telecommunications) - Integrates Scenario E1 with Scenario T2 to evaluate how network reliability affects smart grid monitoring and control

Table **??** provides a summary of all simulation scenarios with their key characteristics.

Table 3.1: Summary of simulation scenarios

Scenario	**Description**	**Duration**	**Time Step**	**Key Metrics**
E1	Smart grid with renewables	24 hours	15 min	Voltage, power flow, curtailment
E2	EV charging impact	24 hours	5 min	Load profile, voltage, charging cost
M1	Urban traffic management	3 hours	1 sec	Travel time, delays, emissions
M2	Autonomous vehicles	2 hours	0.5 sec	Capacity, safety, fuel consumption
T1	5G network slicing	1 hour	Dynamic	Throughput, latency, QoS
T2	Dense IoT network	24 hours	Event	Connection rate, coverage, energy

3.8 Summary

CHAPTER 4

Implementation and Results

This chapter presents the implementation details of the proposed solution and discusses the obtained results. It describes the development process, technical challenges, and evaluates the system's performance against the defined objectives.

4.1 Introduction

4.2 Implementation Overview

4.3 Development Environment

Table 4.1: Development environment and tools

Component	Technology/Tool
Operating System	...
IDE	...
Programming Language	...
Framework	...
Database	...
Version Control	Git

4.4 Implementation Details

4.4.1 Module A Implementation

```python
# Example code snippet
def example_function(param):
    """
    This is an example function
    """
    result = process_data(param)
    return result
```

Código 2: Example implementation of a function

4.4.2 Module B Implementation

4.4.3 Database Schema

4.4.4 API Design

4.5 Technical Challenges

4.5.1 Challenge 1

4.5.2 Challenge 2

4.6 Testing

4.6.1 Unit Testing

4.6.2 Integration Testing

4.6.3 User Acceptance Testing

4.7 Results

4.7.1 Functional Results

figs/results_screenshot.png

Figure 4.1: Example of system output

4.7.2 Performance Results

figs/performance_graph.png

Figure 4.2: Performance evaluation results

4.7.3 Comparative Analysis

4.8 Discussion

4.9 Summary

CHAPTER 5

Conclusions

This chapter presents the conclusions drawn from this work, highlighting the main contributions, discussing limitations, and proposing directions for future work.

5.1 Overview

5.2 Main Contributions

- **Contribution 1:** Description of the first main contribution
- **Contribution 2:** Description of the second main contribution
- **Contribution 3:** Description of the third main contribution

5.3 Objectives Achievement

5.3.1 Objective 1

5.3.2 Objective 2

5.4 Research Questions

5.5 Limitations

- **Limitation 1:** Description and impact
- **Limitation 2:** Description and impact
- **Limitation 3:** Description and impact

5.6 Future Work

5.6.1 Short-term Future Work

5.6.2 Long-term Future Work

5.7 Final Remarks

APPENDIX A

Additional content