Machine Learning Based Propagation Loss Module for Enabling Digital Twins of Wireless Networks in ns-3

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OUTLINE

Introduction

ML-based Propagation Loss (MLPL) Module

Validation of the MLPL Module

Conclusions & Future Work
INTRODUCTION

Next-generation wireless networks require validation & performance evaluation.

**SIMULATION**
- X Medium Accuracy
- ✔ Repeatability
- ✔ Simplicity

**EXPERIMENTAL TESTBED**
- ✔ Perfect Accuracy
- X Cost & Availability
- X Complexity

**DIGITAL TWIN**
- ✔ Reproduction of experimental environment in simulation
- ✔ Accuracy, simplicity and repeatability
NS-3 TRACE-BASED SIMULATION APPROACH

- Propagation loss model based on experimental network traces
  - Replicate experimental environment conditions in simulation at PHY layer
  - Repeatable & reproducible
  - Single and multiple access, SISO, MIMO and Wi-Fi channel occupancy

- Simulation setup = Experimental setup
  - Network traces collected and applied per packet
  - Can not change topology, traffic or duration
## EXISTING APPROACHES FOR VALIDATION

Existing approaches for **extreme scenarios**
(e.g., crowded scenarios, dynamic traffic demands)

|                      | Pure Simulation | Experimental    | Trace-Based                  |
|----------------------|-----------------|-----------------|------------------------------|
| **Accuracy**         | Low (Existing models are generic) | Excellent (Real results) | High (Assuming setup matches) |
| **Repeatability & Reproducibility** | High | Low (Variable environment conditions) | High |
| **Fast-Fading**      | Yes             | Yes             | No                           |
| **Simulation Setup** | Any             | Any             | Exact match (Simulation setup = Experimental setup) |
| **Complexity & Cost**| Low             | High (Limited testbed availability) | Low |
### EXISTING APPROACHES FOR VALIDATION

Existing approaches for **extreme scenarios**
(e.g., crowded scenarios, dynamic traffic demands)

|                      | Pure Simulation | Experimental | Trace-Based       | ML Trace-Based             |
|----------------------|-----------------|--------------|-------------------|----------------------------|
| **Accuracy**         | Low             | Excellent    | High              | High                       |
|                      | Existing models are generic | Real results          | Assuming setup matches | Assuming similar conditions as traces |
| **Repeatability & Reproducibility** | High | Low          | High              | High                       |
|                      |                 | Variable environment conditions |                        | Controlled by RNG seeds |
| **Fast-Fading**      | Yes             | Yes          | No                | Yes                        |
| **Simulation Setup** | Any             | Any          | Exact match       | Any                        |
|                      | Any             | Limited testbed availability | Simulation setup = Experimental setup | Any setup can be used |
| **Complexity & Cost** | Low             | High         | Low               | High                       |
|                      |                 | Limited testbed availability |                  | ML model training |
CONTRIBUTION

- **ML-based Propagation Loss (MLPL) module**
  - Propagation loss model for ns-3 (path loss + fast-fading)
  - ML model trained with experimental network traces

- **Digital twin of experimental wireless network environment**
  - Repeatable and reproducible
  - Any network topology, mobility pattern and duration of simulation
  - Network traces represent environment dynamics
MLPL MODULE

MlPropagationLossModel

Deterministic Path Loss

- Calculated according to distance
- Deterministic value

Stochastic Fast-Fading

- Random value according to CDF
  - Using ns-3 RNG
  - Repeatable & reproducible simulations controlled by ns-3 seed

ML models trained with experimental network traces

E. N. Almeida et al., ”ML Propagation Loss Module for ns-3”, 2022, Available: https://gitlab.com/inesctec-ns3/ml-propagation-loss-model
MLPL MODULE

HELPER SCRIPTS

train_ml_propagation_loss_model.py

- **Train** ML model with dataset
  - Train ML model with external ML framework
  - Save ML model in files

run_ml_propagation_loss_model.py

- **Run** trained ML model
  - Start external ML framework and load ML model
  - Start ns3-ai module
  - Wait for ns-3 simulation to start

- **Using ns3-ai module**
  - Allows using existing ML frameworks
  - Avoids complex integration of ML models directly in ns-3

H. Yin et al., “NS3-AI: Fostering artificial intelligence algorithms for networking research,” in Proceedings of the 2020 Workshop on ns-3, 2020, pp. 57–64.
MLPL MODULE

- **MLPropagationLossModel**
- **MLPropagationLossModelNs3AIDL**
- **ML External Framework**

**Distance (m)**
- **PATH LOSS**
- **TOTAL PROPAGATION LOSS (dB)**
- **ns-3 RNG**
- **FAST-FADING CDF**
- **MLFeature**
  - **Distance (m)**
- **MIPredicted**
  - **Path Loss (dB)**

**INTRODUCTION**

**VALIDATION**

**CONCLUSIONS & FUTURE WORK**
## MLPL DATASET FORMAT

### Simple Data Format
- Distance (m)
- Propagation loss (dB)
  - Path loss + fast-fading

### Raw Data Format
- Nodes coordinates (m)
- Tx power (dBm)
- Antenna gains (dBi)
- Channel frequency (MHz)
- SNR (dB)

### Data pre-processing
- Isolate path loss from fast-fading
- Assuming fast-fading modelled as Normal distribution with $\mu = 0$

- Conversion to Simple Data Format
MLPL MODULE ACCURACY

Compare Propagation Loss Values

MLPL

MLPL Prediction

MLPL’s Accuracy

Real Value

Existing Propagation Loss Model’s Accuracy

Baseline Value

Distance

Network Traces

Existing Propagation Loss Model
MLPL MODULE ACCURACY

TRAINING STRATEGIES

- **Extrapolation**
  - Training Strategy
  - Train: 0-25, Test: 25-25

- **Interpolation**
  - Training Strategy
  - Train: 0-25, Test: 10-20

- **Full Set**
  - Training Strategy
  - Train: 0-25, Test: 0-25

Different datasets for training and testing, collected on the same environment

V. Lamela, H. Fontes, T. Oliveira, J. Ruela, M. Ricardo, and R. Campos, "SIMBED - Offline real-world wireless networking experimentation using ns-3." Zenodo, 2019.
## MLPL Module Accuracy

### Experimental Set-Up

| Wireless Network | Traffic Generated | Nodes & Models |
|------------------|-------------------|----------------|
| IEEE 802.11a     | Distance: [2.07 m, 24.09 m] | 1 Fixed Node + 1 Mobile Node |
| Tx Power: [0 dBm, 12 dBm] | 54 Mbit/s UDP Constant Bitrate | ML Models: SVR and XGB |
| Antenna Gain: -7 dBi | Packet Size: 1400 Bytes | Existing Models: Friis and Log-dist. + Jakes fast-fading |
| Channel: 5220 MHz (20 MHz) | | |
| Warehouse Environment | | |
**MLPL MODULE ACCURACY**

**EXTRAPOLATION TRAINING STRATEGY**

**XGB Most Accurate Model**

**SVR too Optimistic**
MLPL MODULE ACCURACY

INTERPOLATION TRAINING STRATEGY

Accurate Models Despite Training Gaps

Requires Less Data

INTRODUCTION

MLPL MODULE

MLPL VALIDATION

CONCLUSIONS & FUTURE WORK
MLPL MODULE ACCURACY
FULL SET TRAINING STRATEGY

Most Accurate Training Strategy

XGB Able to Predict Spikes
MLPL MODULE EFFECTIVENESS

Compare Network Performance

Distance

Network Traces

Existing Propagation Loss Model

MLPL

MLPL Prediction

Real Value

Baseline Value

MLPL’s Performance

Existing Propagation Loss Model’s Performance
# MLPL Module Effectiveness

**NS-3.35 Simulation Parameters**

| Wireless Network | Traffic Generated | Nodes & Models |
|------------------|-------------------|----------------|
| IEEE 802.11a     | Distance: [2.07 m, 24.09 m] | 1 Fixed Node + 1 Mobile Node |
| Tx Power: 7 dBm  | 54 Mbit/s UDP Constant Bitrate | ML Training Strategy: Full Set |
| Antenna Gain: -7 dBi | Packet Size: 1400 Bytes | Existing Models: Friis and Log-dist. + Jakes fast-fading |
| Channel: 5220 MHz (20 MHz) | Simulation Duration: 404 s | |
| Preamble Threshold: -90 dBm | | |
MLPL MODULE EFFECTIVENESS

MLPL NETWORK PERFORMANCE

- **XGB**
  - Most accurate ML model
  - Reproduce data spread
  - Optimistic for longer distances

- **SVR**
  - Follow general trend
  - Too optimistic

- **Friis and Log-distance**
  - Too optimistic
  - Do not reproduce goodput spread
CONCLUSIONS

▪ ML-based Propagation Loss (MLPL) Module for ns-3
  – Digital twin of experimental wireless environment
  – Trained with experimental network traces
  – Repeatable, reproducible and flexible

▪ More accurate than existing models
  – Especially in highly dynamic scenarios
FUTURE WORK

- Improve ML model accuracy
- Consider more parameters

Publish in ns-3 App Store
- Module already available on GitLab
- Finish user API of ML helper scripts
- ETA: Few weeks after WNS3 2022

E. N. Almeida et al., "ML Propagation Loss Module for ns-3", 2022, Available: https://gitlab.com/inesctec-ns3/ml-propagation-loss-model
QUESTIONS?

Machine Learning Based Propagation Loss Module for Enabling Digital Twins of Wireless Networks in ns-3

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E. N. Almeida et al., "ML Propagation Loss Module for ns-3", 2022, Available: https://gitlab.com/inesctec-ns3/ml-propagation-loss-model

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