Workshop on ns-3 2022
22 – 23 June 2022 | Virtual Event

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

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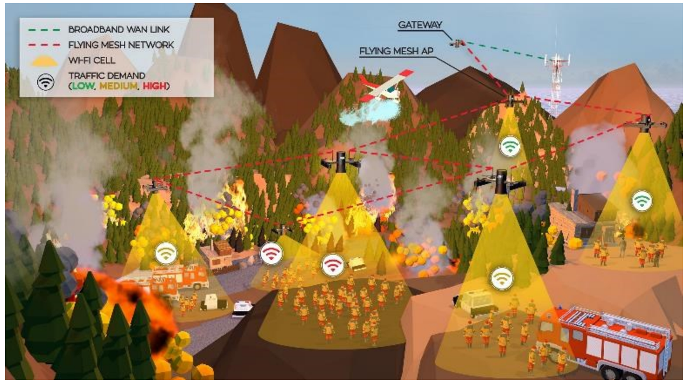
OUTLINE

INTRODUCTION

Next-generation wireless networks require validation & performance evaluation

SIMULATION

- ✗ Medium Accuracy
- ✓ Repeatability
- ✓ Simplicity



EXPERIMENTAL TESTBED

- ✓ Perfect Accuracy
- ✗ Cost & Availability
- ✗ Complexity

ns-3 ⟳

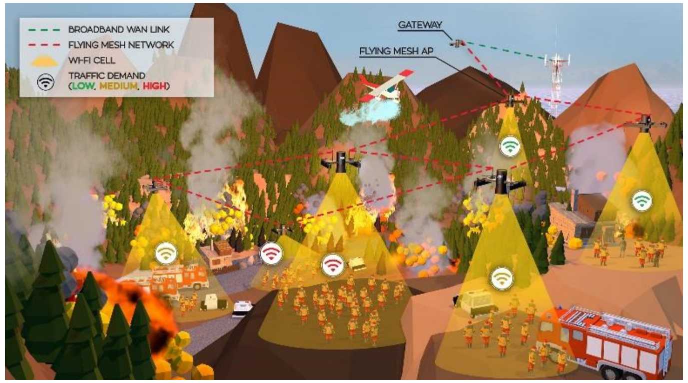
DIGITAL TWIN

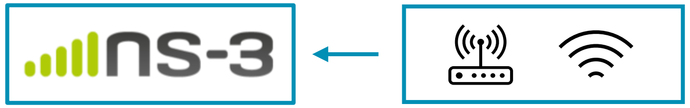
- ✓ Reproduction of experimental environment in simulation
- ✓ Accuracy, simplicity and repeatability

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

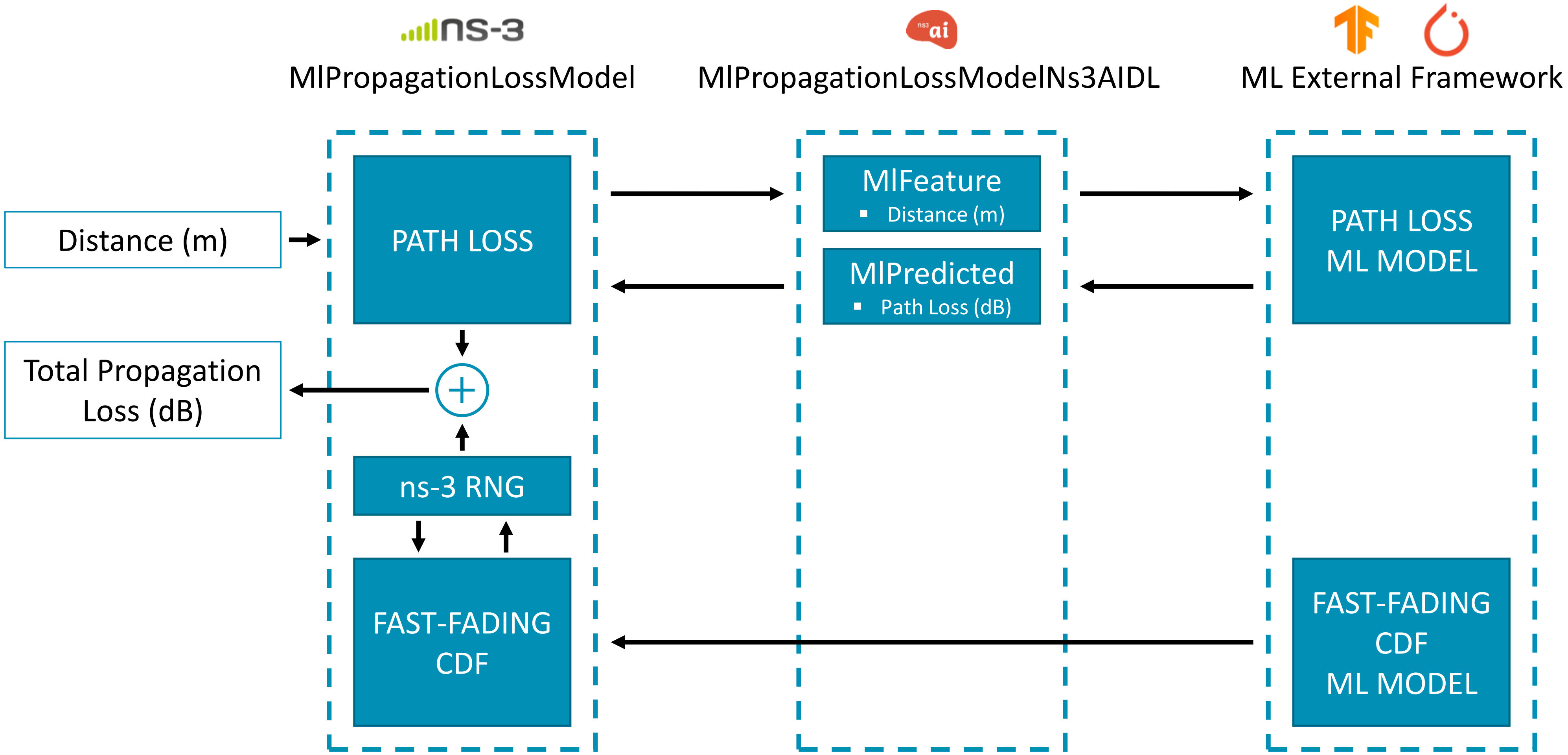
run_ml_propagation_loss_model.py

- 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)
MlPredicted
Path Loss (dB)
PATH LOSS ML MODEL
FAST-FADING CDF ML MODEL

MLPL DATASET FORMAT

Simple Data Format

- Distance (m)
- Propagation loss (dB)
  - Path loss + fast-fading

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

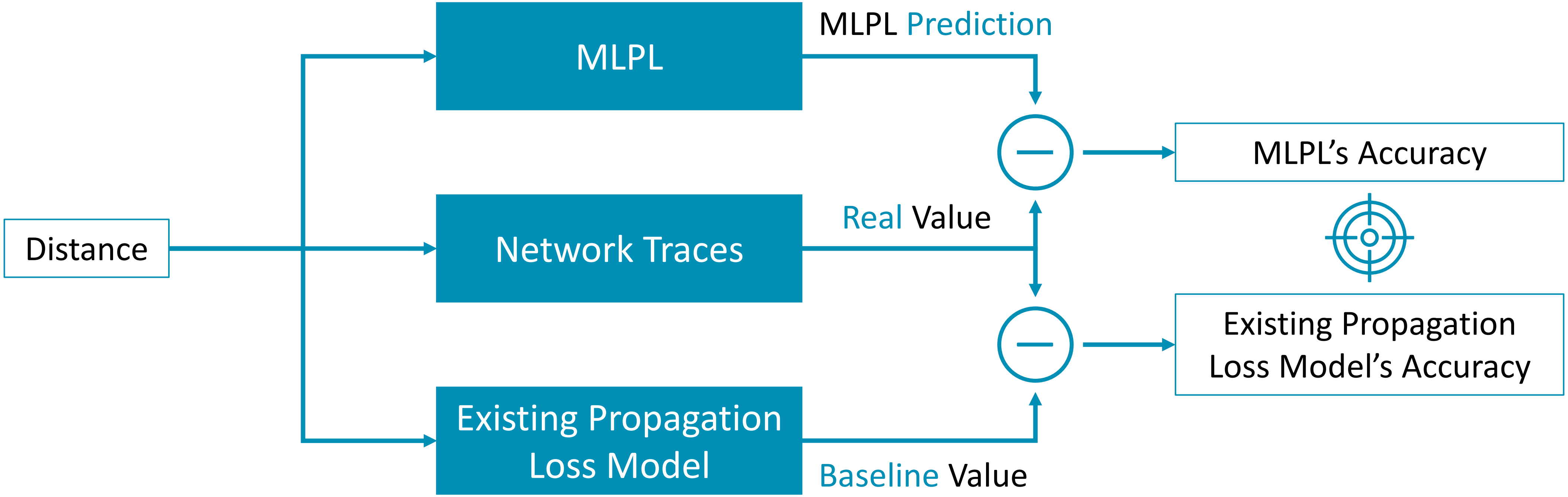
Raw Data Format

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

- Data pre-processing
  - Conversion to Simple Data Format

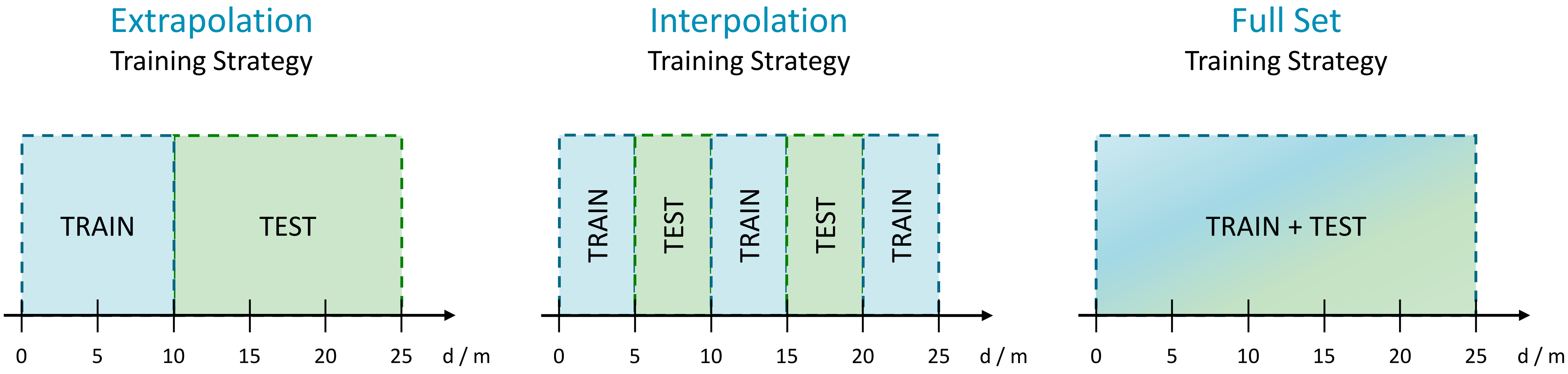
MLPL MODULE ACCURACY

Compare Propagation Loss Values



MLPL MODULE ACCURACY

TRAINING STRATEGIES



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

- IEEE 802.11a
- Tx Power: [0 dBm, 12 dBm]
- Antenna Gain: -7 dBi
- Channel: 5220 MHz (20 MHz)
- Warehouse Environment

Traffic Generated

- Distance: [2.07 m, 24.09 m]
- 54 Mbit/s UDP Constant Bitrate
- Packet Size: 1400 Bytes

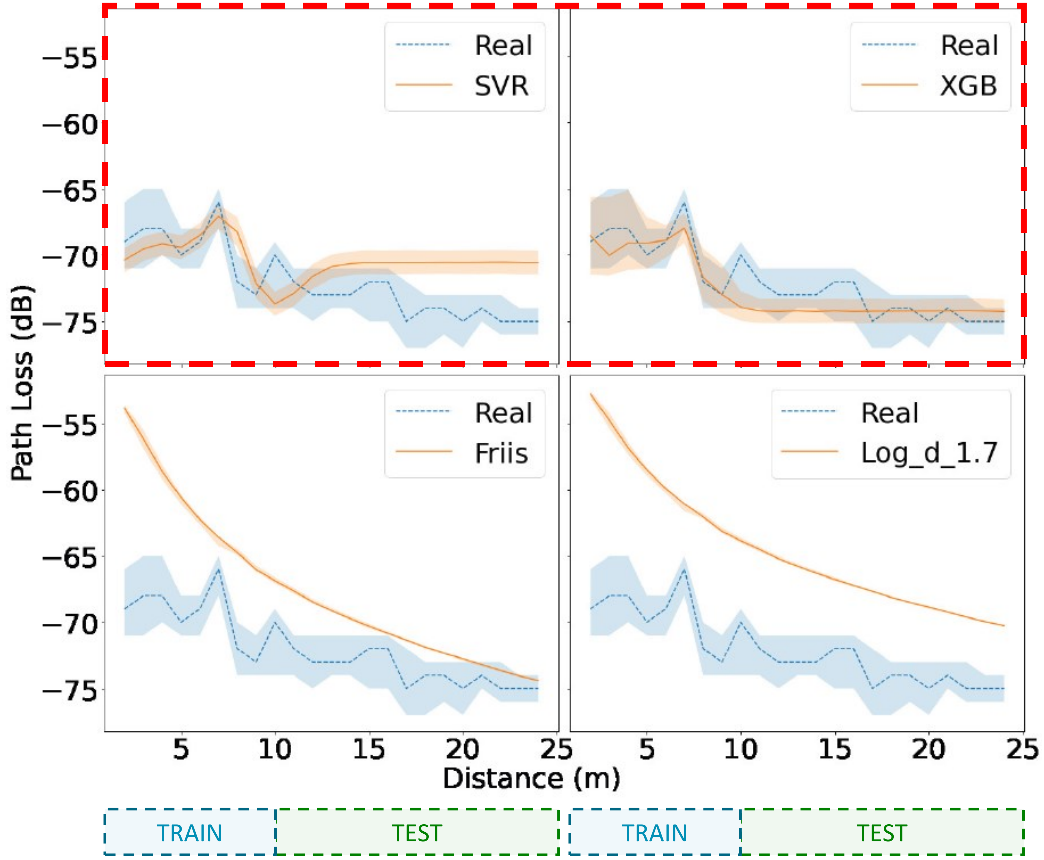
Nodes & Models

- 1 Fixed Node + 1 Mobile Node
- ML Models: SVR and XGB
- Existing Models: Friis and Log-dist. + Jakes fast-fading

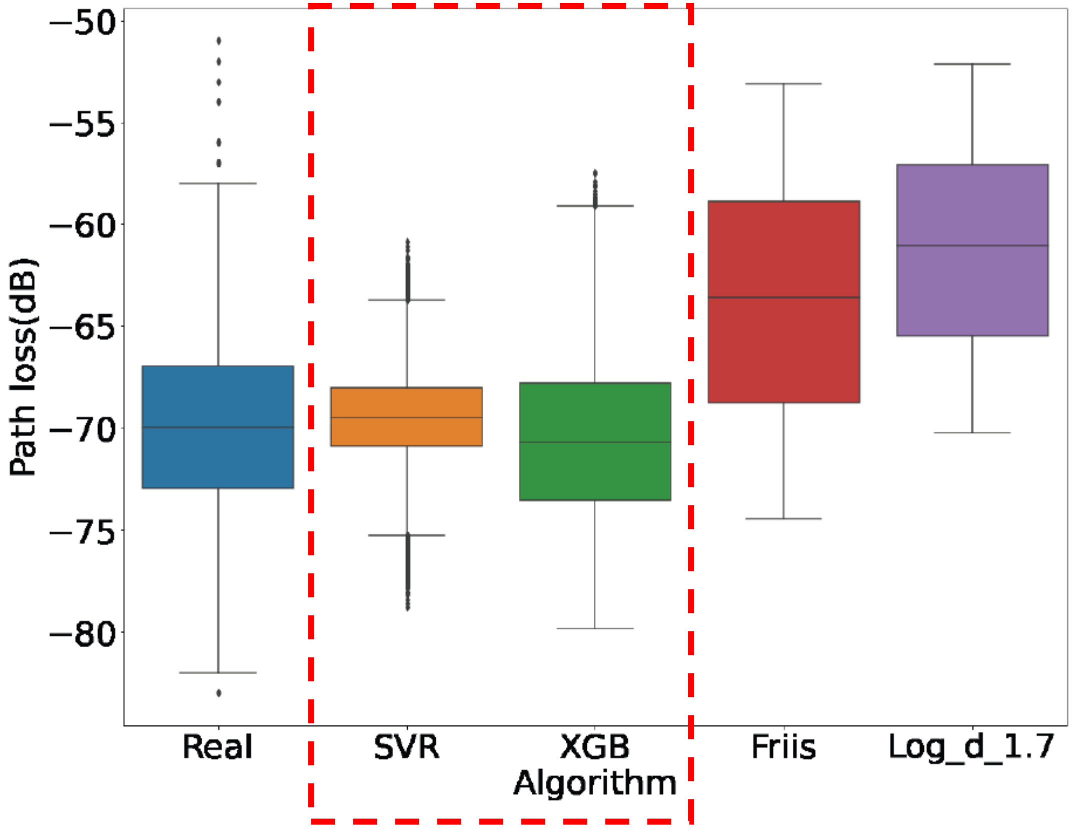
MLPL MODULE ACCURACY

EXTRAPOLATION TRAINING STRATEGY

XGB Most Accurate Model



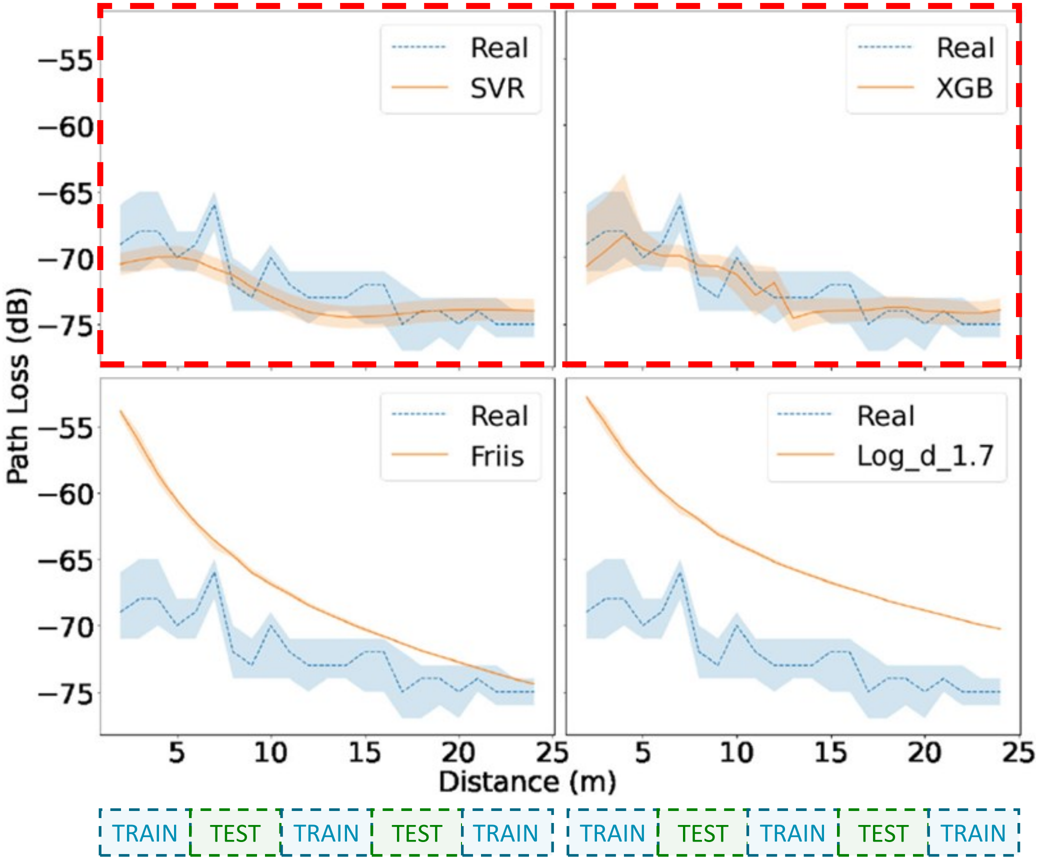
SVR too Optimistic



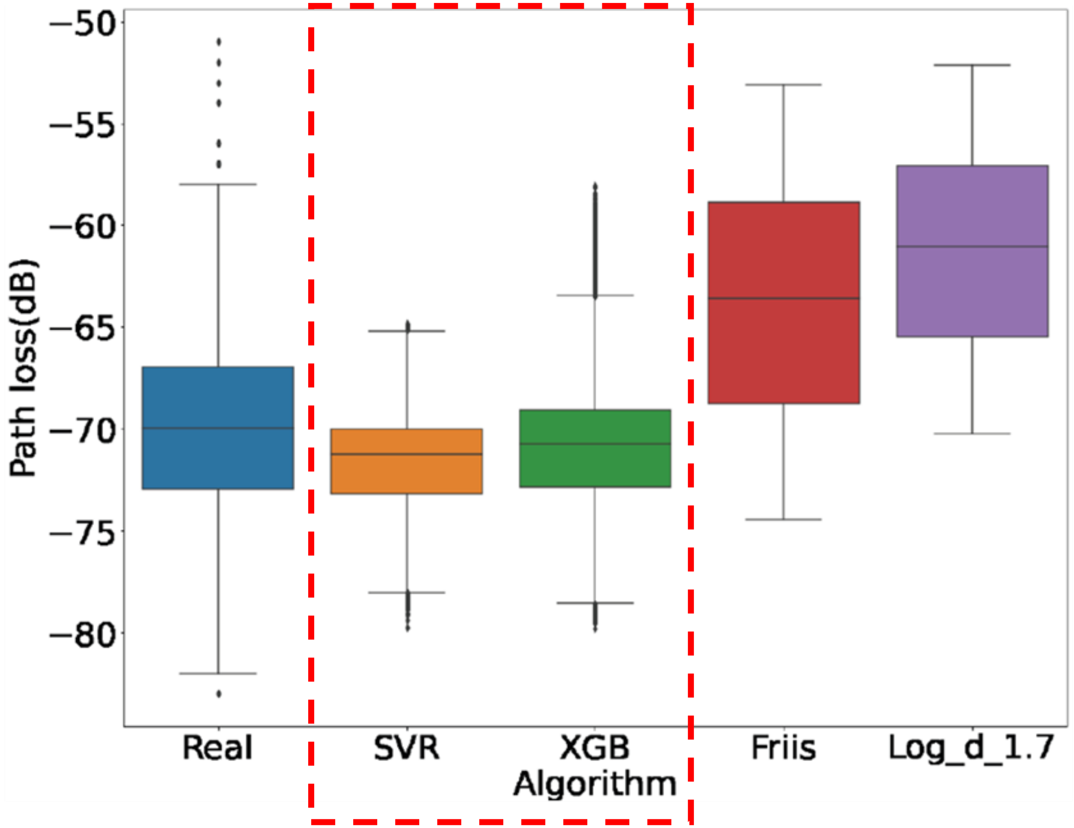
MLPL MODULE ACCURACY

INTERPOLATION TRAINING STRATEGY

Accurate Models Despite Training Gaps



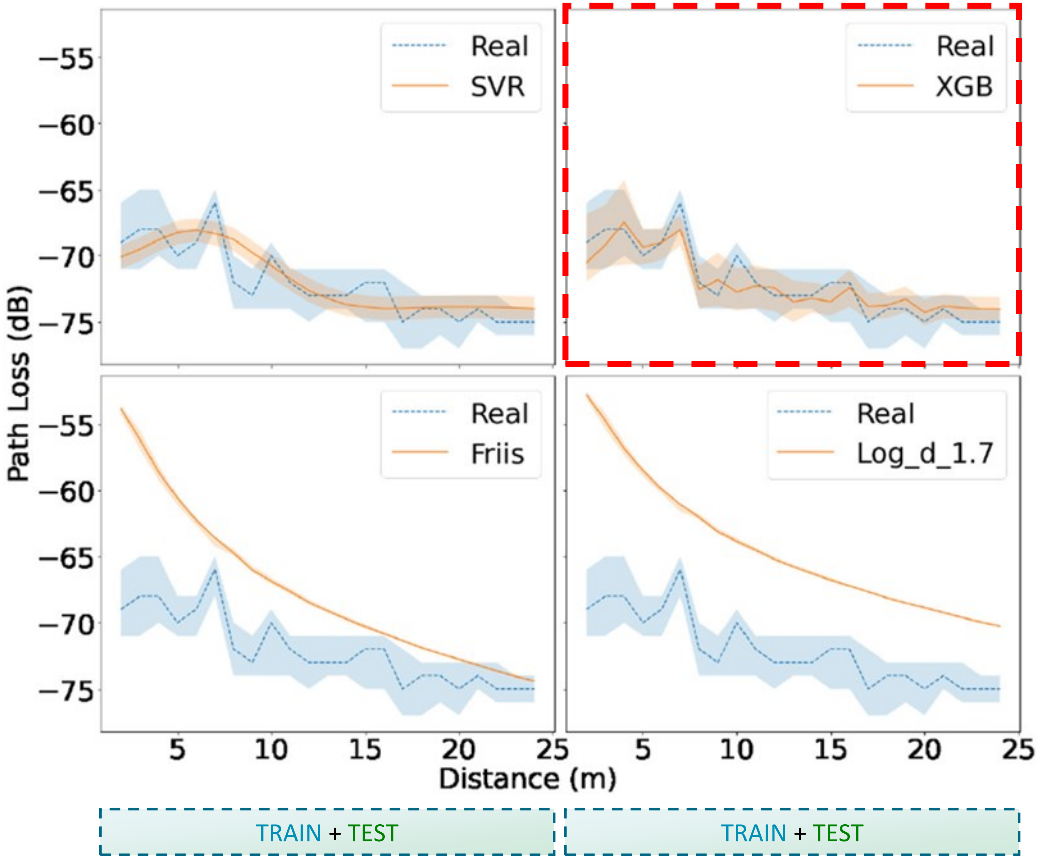
Requires Less Data



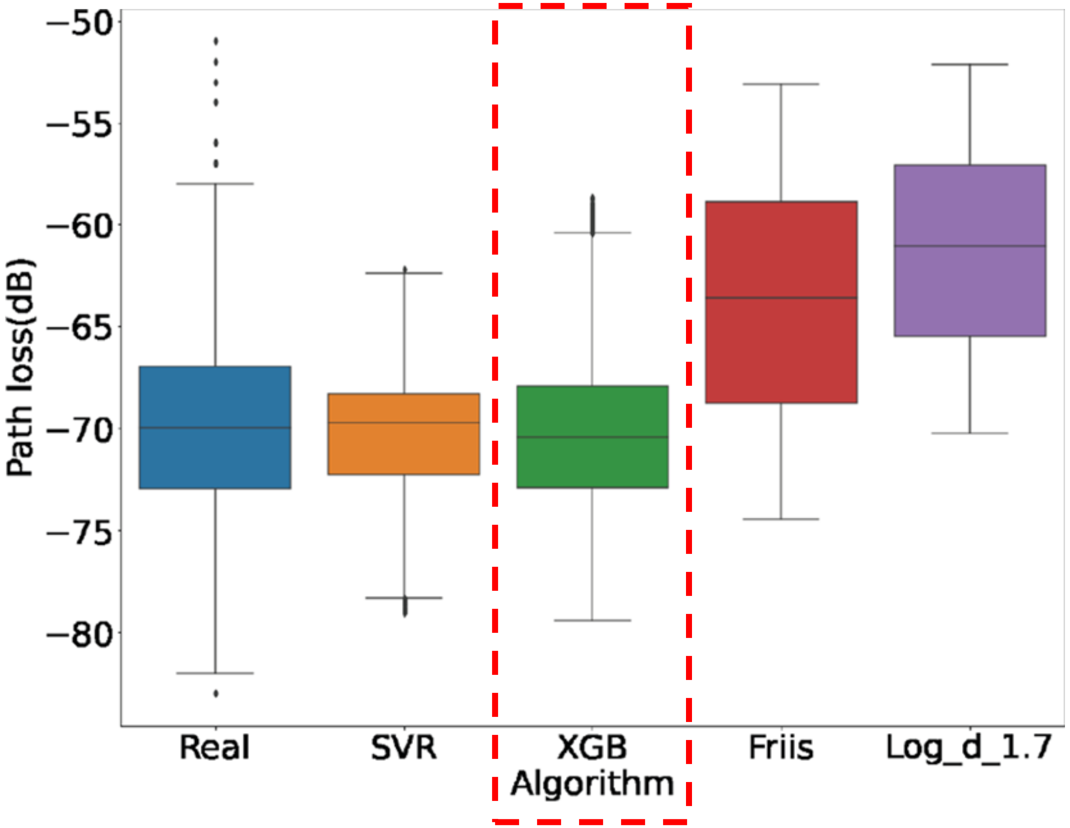
MLPL MODULE ACCURACY

FULL SET TRAINING STRATEGY

Most Accurate Training Strategy

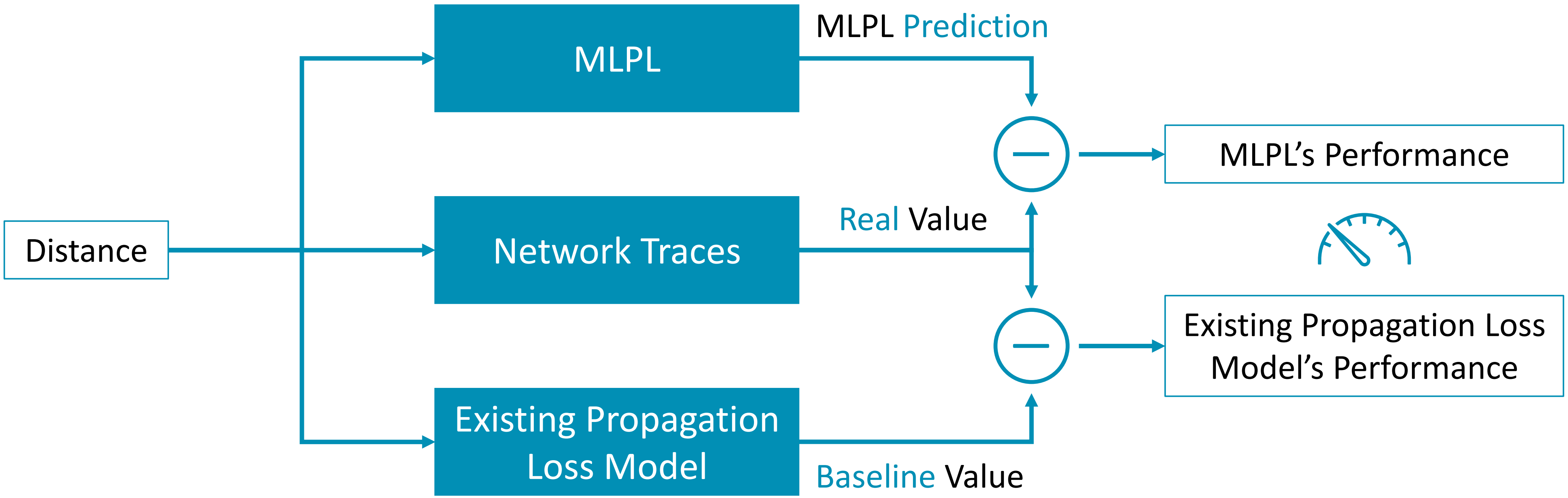


XGB Able to Predict Spikes



MLPL MODULE EFFECTIVENESS

Compare Network Performance



MLPL MODULE EFFECTIVENESS

NS-3.35 SIMULATION PARAMETERS

Wireless Network

- IEEE 802.11a
- Tx Power: 7 dBm
- Antenna Gain: -7 dBi
- Channel: 5220 MHz (20 MHz)
- Preamble Threshold: -90 dBm

Traffic Generated

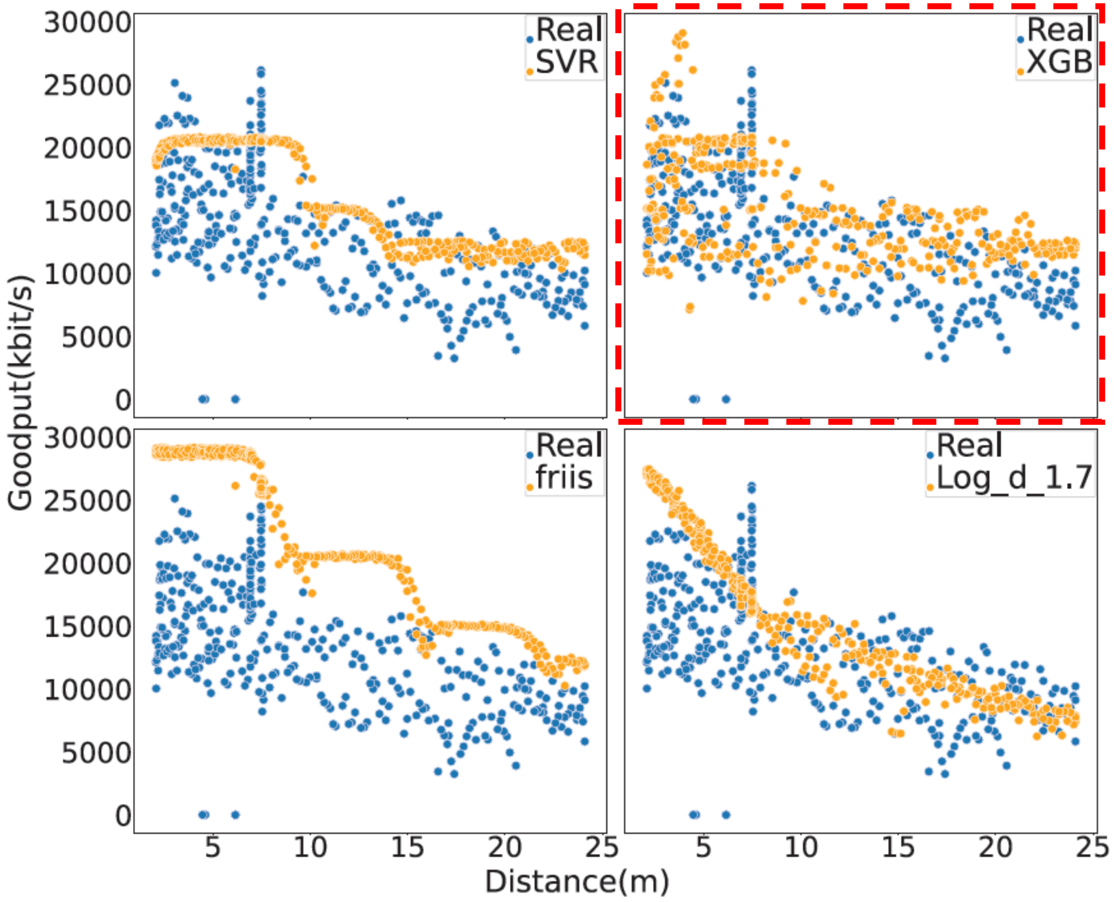
- Distance: [2.07 m, 24.09 m]
- 54 Mbit/s UDP Constant Bitrate
- Packet Size: 1400 Bytes
- Simulation Duration: 404 s

Nodes & Models

- 1 Fixed Node + 1 Mobile Node
- ML Training Strategy: Full Set
- Existing Models: Friis and Log-dist. + Jakes fast-fading

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

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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

Acknowledgments

This article is a result of the project "DECARBONIZE – DEvelopment of strategies and policies based on energy and non-energy applications towards CARBON neutrality via digitalization for citIZEns and society" (NORTE-01-0145-FEDER-000065), supported by Norte Portugal Regional Operational Programme (NORTE 2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund (ERDF).