Novel ns-3 Model Enabling Simulation of Electromagnetic Wireless Underground Networks

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Outline

• Introduction
• Objectives
• Underground propagation models
• Work methodology
• Results
• Conclusions
Introduction - WUN

- **Wireless Underground Networks (WUN)** consist of
  - Nodes buried underground and aboveground
  - Wireless links
  - Two Propagation media

- **4 types of links**
  - Underground-to-Underground (U2U)
  - Aboveground-to-Aboveground (A2A)
  - Underground-to-Aboveground (U2A)
  - Aboveground-to-Underground (A2U)
Introduction - WUN

- Playing fields, Agriculture
  - Monitor soil water content, temperature
  - Automatically control irrigation systems
- Security
  - Border surveillance
- Infrastructure monitoring
  - Pipeline monitoring

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Introduction - ns-3

• No network simulators available for WUN

• ns-3 characteristics
  – Open source
  – Experience in our research group in using ns-3
  – Highly modular
  – Well documented
  – Allow easily integration of user implemented models
  – Well accepted by the research community

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Objectives of the work

- Study existing underground propagation models
- Improve ns-3 towards WUN
- Validate ns-3 models against results obtained in testbeds
Path loss in soils

• Free Space Path Loss, Friis equation [dB]

\[ P_r = P_t + G_t + G_r - L_0, \quad L_0 = 10 \log \left( \frac{4\pi d}{\lambda_0} \right)^2 \]

• Path Loss in Soil

\[ P_r = P_t + G_t + G_r - L_p, \quad L_p = L_0 + L_{\text{soil}}, \quad L_{\text{soil}} = L_\beta + L_\alpha \]

  - Propagation constant (in soil)
    - \[ \gamma = \alpha + j\beta \]
    - \[ \gamma \] depends on soil dielectric properties \( \rightarrow \) type soil, water content
  - Attenuation constant \( \alpha \) [m\(^{-1}\)]
  - Phase constant \( \beta \) [rad.m\(^{-1}\)] \( \rightarrow \lambda = \frac{2\pi}{\beta} \) \( \rightarrow v = \lambda f \)

\[ L_\beta = 10 \log \left( \frac{\lambda_0}{\lambda} \right)^2, \quad L_\alpha = 10 \log e^{2\alpha d} \]
Two-ray U2U model

- Single direct ray

  \[ L_{sl} = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d - 10\log(G_a G_b) \]

- Two-rays

\[ L_{fl} = L_{sl} - 10\log \left| 1 + \frac{\sqrt{G_c G_d R d e^{\alpha \Delta r}}}{\sqrt{G_a G_b (r_1 + r_2)}} e^{-j\Delta \phi} \right|^2 \]

\[ \Delta r = r_1 + r_2 \quad \Delta \phi = \frac{2\pi \Delta r}{\lambda} \quad R: \text{reflection coefficient soil–air} \]
Three-ray U2U model

\[ P_d = P_t + 20 \log \lambda_s - 20 \log r1 - 8.69ar1 - 45 \]

\[ Pr = P_t + 20 \log \lambda_s - 20 \log r2 - 8.69ar2 + 20 \log \Gamma - 45 \]

\[ Pl = P_t + 20 \log \lambda_s - 40 \log dh - 8.69\alpha(ht + hr) + 20 \log T - 30 \]

\[ Pr = 10 \log \left( \frac{P_d}{10} + \frac{Pr}{10} + \frac{Pl}{10} \right) \]
A2U model

\[ L_a = 20 \log f + 20 \log d1 - 147.56 \]

\[ L_u = 6.4 + 20 \log d2 + 20 \log \beta + 8.69ad2 \]

\[ L_{a-u} = 10 \log \frac{(\cos \theta i + \sqrt{\varepsilon' - \sin^2 \theta i})^2}{4 \cos \theta i \sqrt{\varepsilon' - \sin^2 \theta i}} \]

\[ L_{total} = L_a + L_u + L_{a-u} - 10 \log \chi^2 \]

- Rayleigh distribution
U2A model

\[ L_a = 20 \log f + 20 \log d2 - 147.56 \]

\[ L_u = 6.4 + 20 \log d1 + 20 \log \beta + 8.69 \alpha d1 \]

\[ L_{u-a} = 10 \log \left( \frac{\sqrt{\varepsilon'} - 1}{4 \sqrt{\varepsilon'}} \right)^2 \]

\[ L_{total} = L_u + L_a + L_{u-a} - 10 \log \chi^2 \]

- Rayleigh distribution
Methodology

• Include propagation models into ns-3
• Develop a new Wi-Fi channel with two propagation media
  – Soil propagation medium
  – Air propagation medium
• Carry-out network simulations using the new models
• Compare simulation results against testbed results previously obtained at INESC TEC
• Conclude about validity of models
New models in ns-3

• Estimate soil dielectric constant
  – estimateSoilDielectricConstantSMDM
  – estimateSoilDielectricConstantMBSDM
  – Based on type of soil and water volume contents

• Estimate path loss between two nodes
  – ns3::UndergroundPathLossModel
  – U2U: 2 and 3 ray models
  – Hybrid: U2A e A2U
  – A2A

• Estimate propagation delay between two nodes
  – ns3::UndergroundConstantSpeedPropagationDelayModel
  – Using velocity of EM wave in the soil,
    \[ t = \frac{d}{v} = \frac{d}{\lambda f} = \frac{\beta}{2\pi f} d \]
New models in ns-3

• New Wi-Fi channel
  – ns3::UndergroundWifiChannel
  – Supports two different propagation media
  – Use underground path loss model for underground links
  – Reuse ns-3 propagation models for over the air links

• New Wi-Fi phy
  – ns3::UndergroundWifiPhy
  – Uses the ns3::UndergroundWifiChannel
  – Similar to the ns3::YansWifiPhy

• New Wi-Fi helper
  – ns3::UndergroundWifiPhyHelper
  – ns3::UndergroundWifiChannelHelper

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New models in ns-3

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Simulations – network topologies

- 2 nodes, single wireless link
- Nodes running UDP/IP/802.11g
- Traffic source: ns-3 OnOff (CBR)
- Traffic sink: ns-3 DataSink
- Bands: 2.4 GHz | 433 MHz
Simulations – network topologies

- Transmission power: 20 dBm
- Antenna gain: 2 dBi (transmitter)
- Antenna gain: 3 dBi (receiver)
- U2U: 2 nodes buried at 20 | 30 cm
- U2A, A2U: node buried at 35 cm
- Air node at 2.5 m height
- Soil: loam
Simulations – metrics

• Performance metrics
  – RSSI
  – Throughput
  – Packet Loss Ratio (PLR)
  – Delay
  – Delay Jitter

• Measured using ns-3 Flow monitor
Simulation results - U2U, 2.4 GHz, RSSi

- RSSi difference 2 ray: 11 dBm @ 20 cm | 14 dBm @ 30 cm
- RSSi difference 3 ray: 5 dBm @ 20 cm | 8 dBm @ 30 cm
- Distance difference 3 ray: 21% @ 20 cm | 21% @ 30 cm
- 2-ray model not adequate for high horizontal distances
  - Lateral wave is the dominant component (d > 1m)
  - 3 ray model should be used
Simulation results - U2U, 2.4 GHz, Throughput

- Difference 2 ray: 4.5 Mbit/s @ 20 cm | 5 Mbit/s @ 30 cm
- Difference 3 ray: 7 Mbit/s @ 20 cm | 4 Mbit/s @ 30 cm
- Higher precision for high depths
- 2 ray model with results only until 1.1 m
Simulation results - U2U, 2.4 GHz, Delay

- Experimental results with ping – Round-trip time (RTT)
- Simulation results measure packet delay
Simulation results - U2U, 2.4 GHz, Jitter

- Difference 2 ray: 0.06 ms @ 20 cm | 0.04 ms @ 30 cm
- Difference 3 ray: 0.12 ms @ 20 cm | 0.11 ms @ 30 cm
- Higher precision for high depths
- 2 ray model with results only until 1.1 m
Simulation results - U2A, A2U, 433 MHz

- Air node at 2.5 m height | Underground node at 35 cm
- No Rayleigh: RSSi difference: 4 dBm @ U2A | 10 dBm @ A2U
- Rayleigh: RSSi difference: 3 dBm @ U2A | 9.5 dBm @ A2U
- Multi path component introduces channel variability
Simulation results - discussion

- Lateral wave is the dominant component for
  - lower depths (< 20cm) and
  - high horizontal distances (> 1m)
- Models more accurate for higher depths
- Hybrid model accurate with and without multipath
Conclusions / Contributions

- ns-3 discrete event simulator for Wireless Underground Networks
- Validation of models (theoretical propagation + ns-3) against experimental results
- Code publicly available at https://telecom.inescporto.pt/~sconceicao/sourcecode.zip
Future work

- Improve hybrid propagation models (U2A, A2U)
- Evaluate multi-access and multi-hop underground scenarios using ns-3
- Improve communication stack for WUN
- Include the underground model in a future ns-3 release
Thanks!