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

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WNS3 2015, Barcelona, Spain

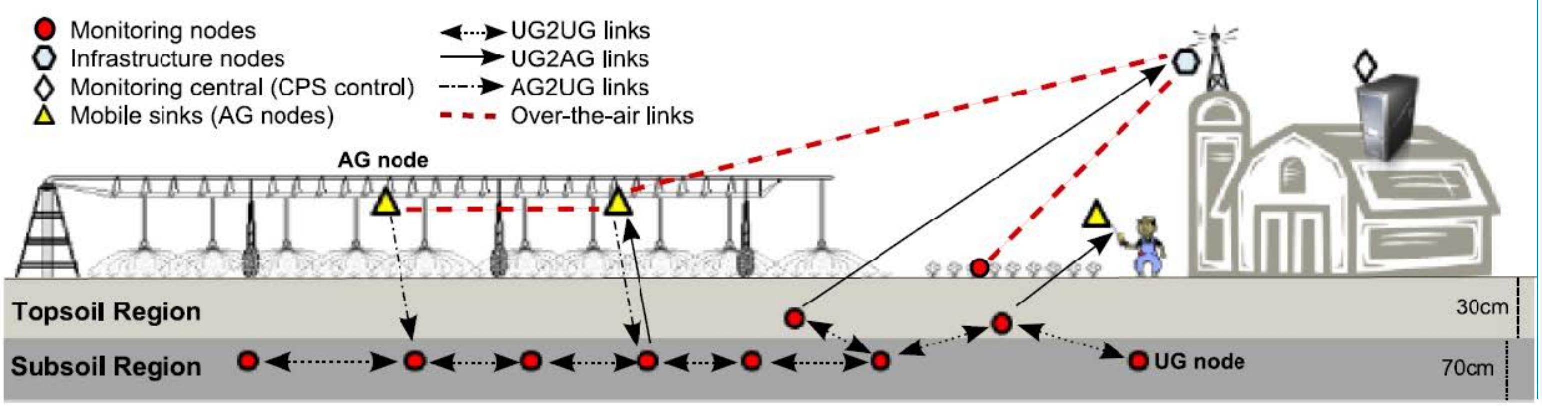
13th May 2015

Outline

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

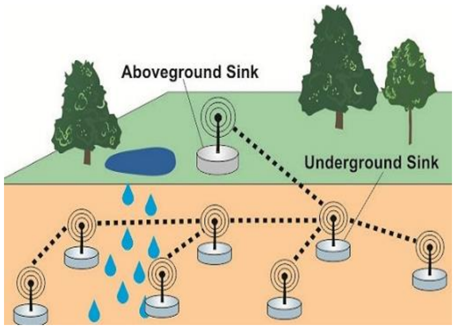
Introduction - WUN

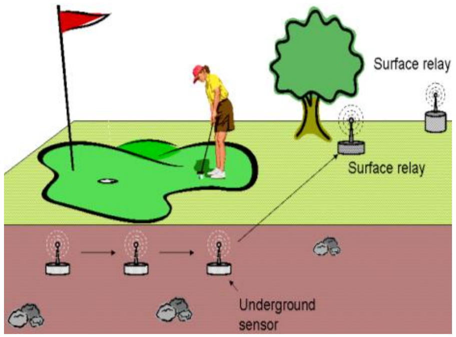
- Wireless Underground Networks (**WUN**) consist of
  - Nodes buried underground and aboveground
  - Wireless links
  - Two Propagation media
- 4 types of links
  - Underground-to-Underground (U2U)
  - Aboveground-to-Aboveground (A2A)
  - Underground-to-Aboveground (U2A)
  - Aboveground-to-Underground (A2U)

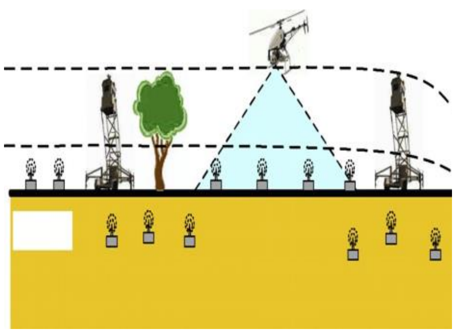


Introduction - WUN

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

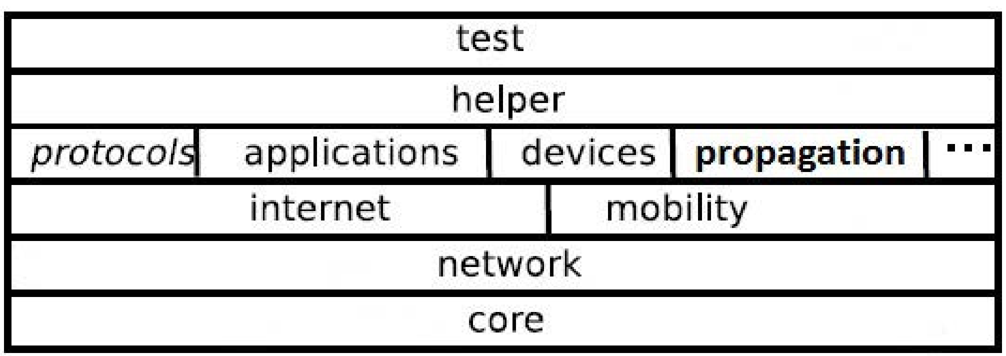






Introduction - ns-3

- 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



Objectives of the work

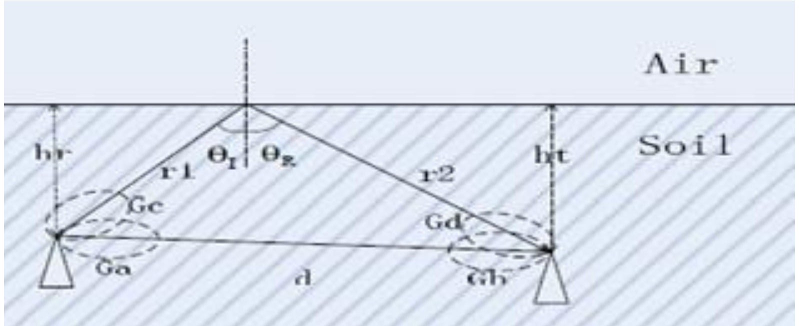
- Study existing underground propagation models
- Improve ns-3 towards WUN
- Validate ns-3 models against results obtained in testbeds

Path loss in soils

- Free Space Path Loss, Friis equation [dB]
  - $P_r = P_t + G_t + G_r - L_0$, $L_0 = 10\ \log\left(\frac{4\pi d}{\lambda_0}\right)^2$
- Path Loss in Soil
  - $P_r = P_t + G_t + G_r - L_p$, $L_p = L_0 + L_{soil}$, $\boldsymbol{L_{soil} = L_\beta + L_\alpha}$
  - Propagation constant (in soil)
    - $\gamma = \alpha + j\beta$
    - γ **depends on soil dielectric properties → type soil, water content**
  - Attenuation constant α $[m^{-1}]$
  - Phase constant β $[rad.m^{-1}]$ $\rightarrow \lambda = \frac{2\pi}{\beta}$ $\rightarrow \text{v} = \lambda f$
  - $L_\beta = 10\ \log\left(\frac{\lambda_0}{\lambda}\right)^2$, $L_\alpha = 10\ \log e^{2\alpha d}$

Two-ray U2U model

- Single direct ray
  - *Lsl* = $L_{sl} = 6.4 + 20log(d) + 20log(\beta) + 8.69\alpha d - 10log(G_a G_b)$

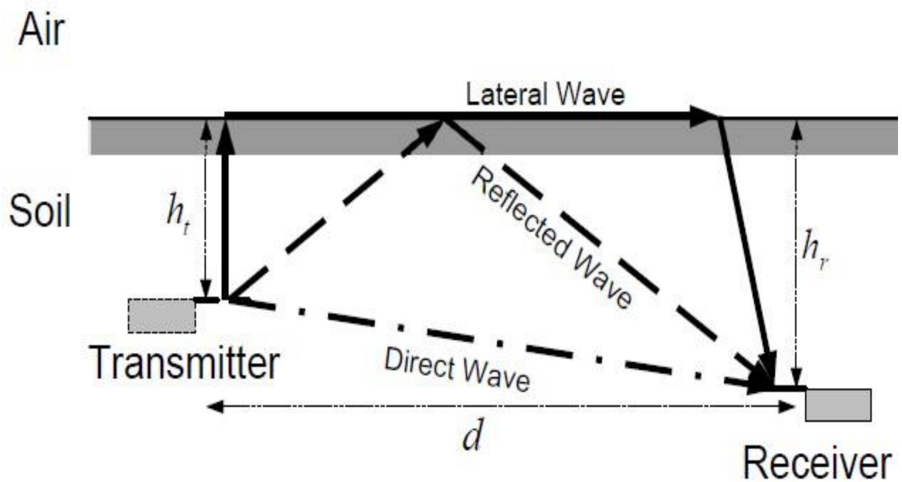


- Two-rays

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

$\Delta r = r_1 + r_2$ | $\Delta\phi = \frac{2\pi\Delta r}{\lambda}$ | R: reflection coefficient soil–air

Three-ray U2U model



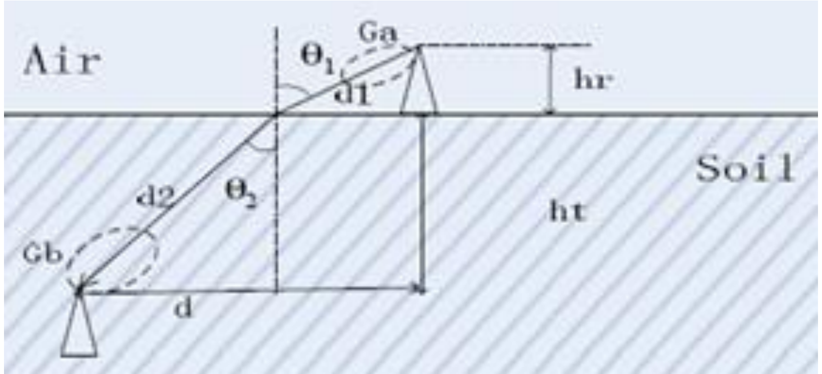
$$Pd = Pt + 20\log\lambda_s - 20\log r1 - 8.69\alpha r1 - 45$$

$$Pr = Pt + 20\log\lambda_s - 20\log r2 - 8.69\alpha r2 + 20log\Gamma - 45$$

$$Pl = Pt + 20\log\lambda_s - 40\log dh - 8.69\alpha(ht + hr) + 20logT - 30$$

$$\boldsymbol{Pr = 10\log(10^{\frac{Pd}{10}} + 10^{\frac{Pr}{10}} + 10^{\frac{Pl}{10}})}$$

A2U model



$$L_a = 20\log f + 20\log d1 - 147.56$$

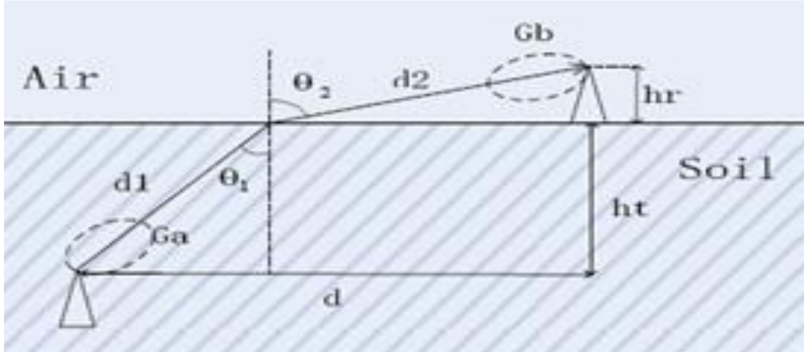
$$L_u = 6.4 + 20\log d2 + 20\log \beta + 8.69\alpha d2$$

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

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

- **Rayleigh distribution**

U2A model



$$L_a = 20\log f + 20\log d2 - 147.56$$

$$L_u = 6.4 + 20\log d1 + 20\log \beta + 8.69\alpha d1$$

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

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

- **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

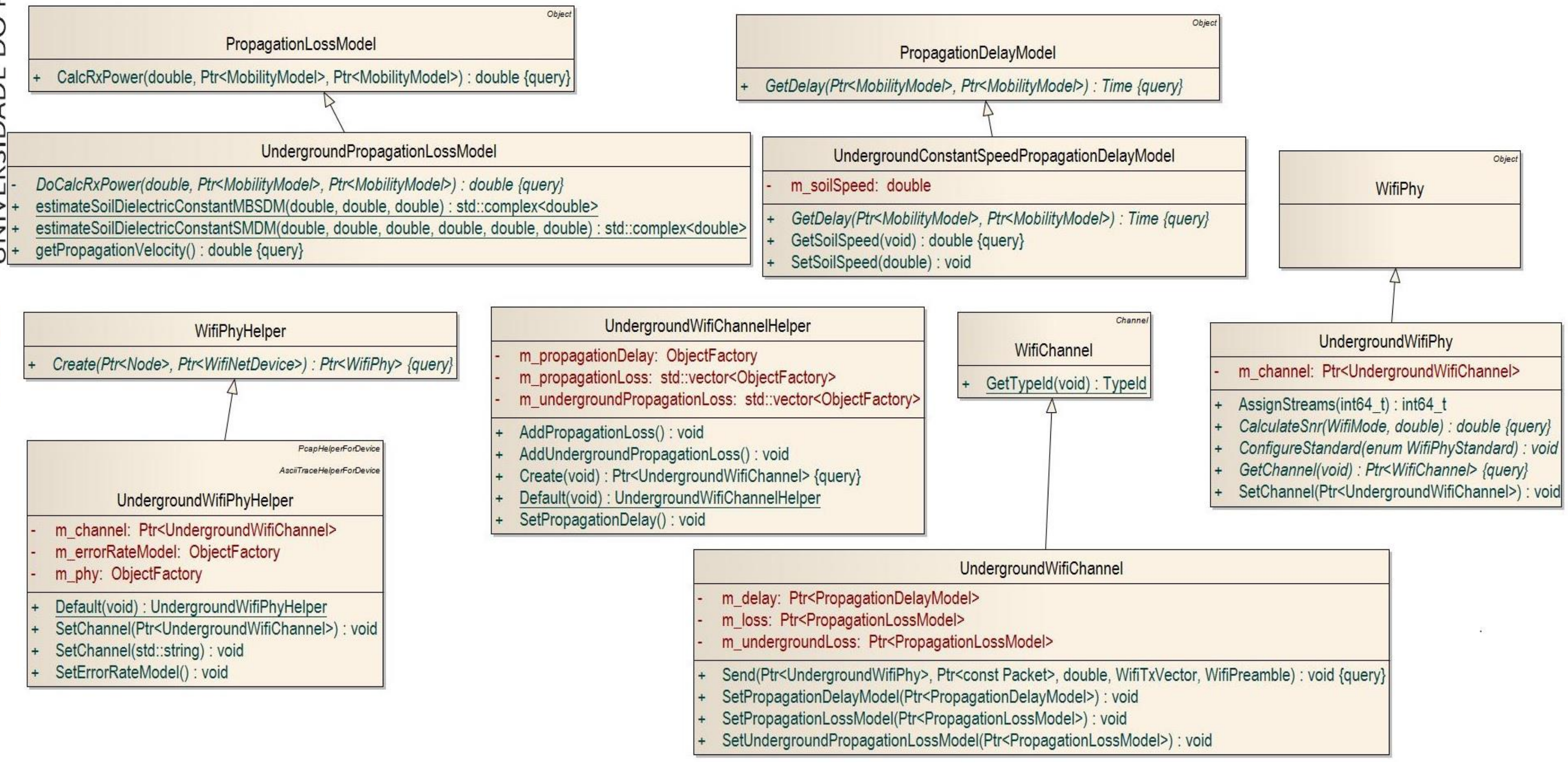
- Estimate path loss between two nodes
  - **ns3::UndergroundPathLossModel**
  - U2U: 2 and 3 ray models
  - Hybrid: U2A e A2U
  - A2A

- 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

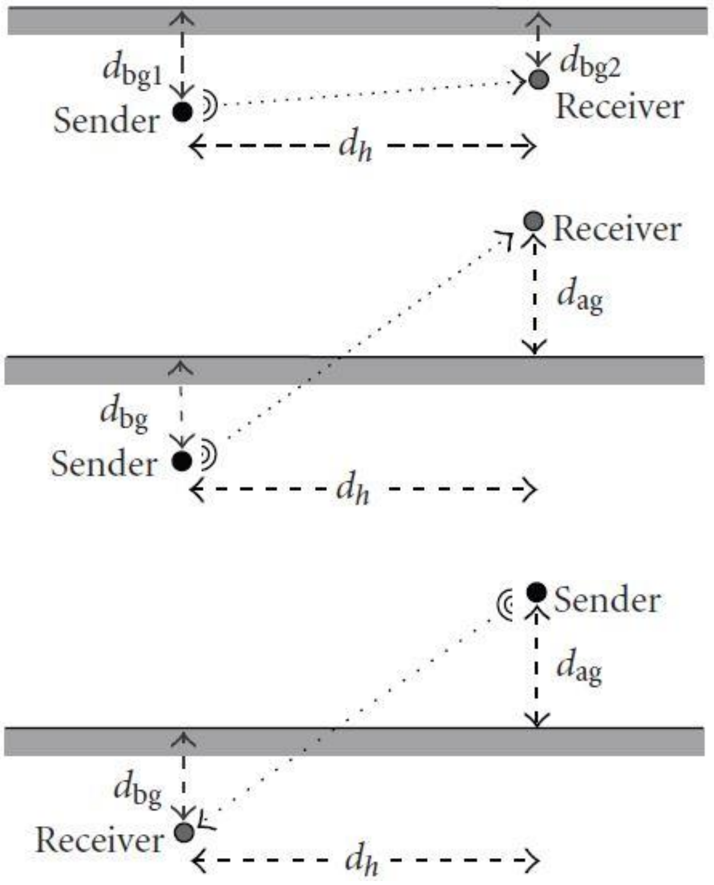
- New Wi-Fi channel
  - **ns3::UndergroundWifiChannel**
  - Supports two different propagation media
  - Use underground path loss model for underground links
  - Reuse ns-3 propagation models for over the air links
- New Wi-Fi phy
  - **ns3::UndergroundWifiPhy**
  - Uses the ns3::UndergroundWifiChannel
  - Similar to the ns3::YansWifiPhy
- New Wi-Fi helper
  - **ns3::UndergroundWifiPhyHelper**
  - **ns3::UndergroundWifiChannelHelper**

New models in ns-3



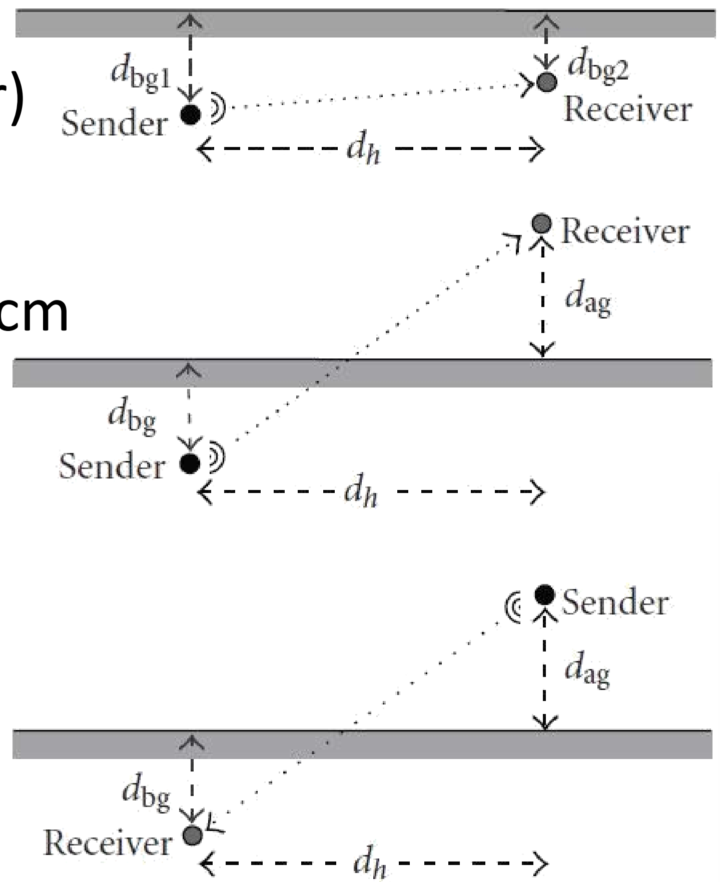
Simulations – network topologies

- 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

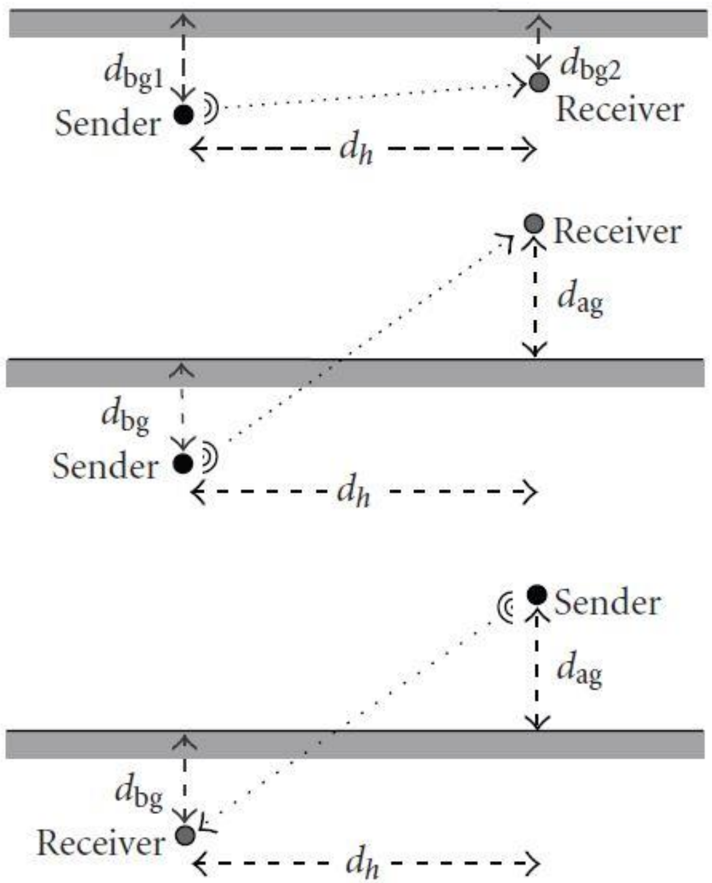
- Transmission power: 20 dBm
- Antenna gain: 2 dBi (transmitter)
- Antenna gain: 3 dBi (receiver)
- U2U: 2 nodes buried at 20 | 30 cm
- U2A, A2U: node buried at 35 cm
- Air node at 2.5 m height
- Soil: loam



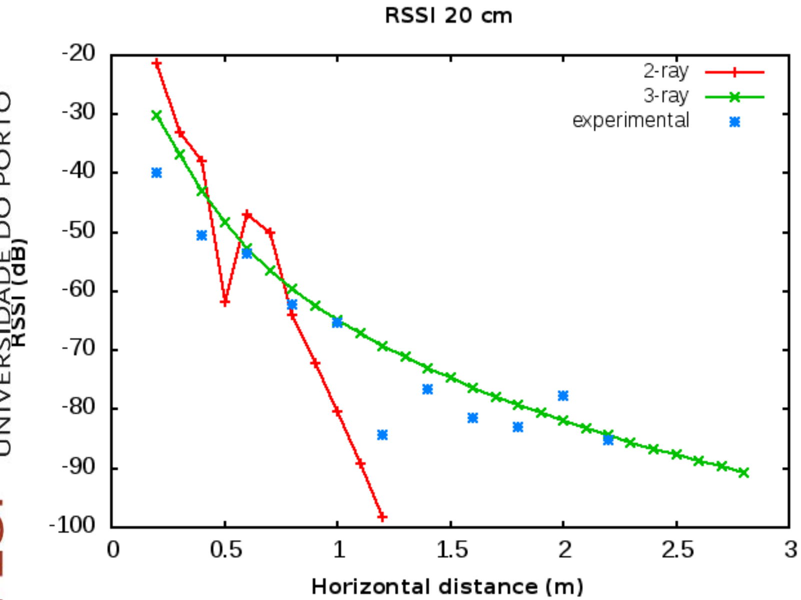
Simulations – metrics

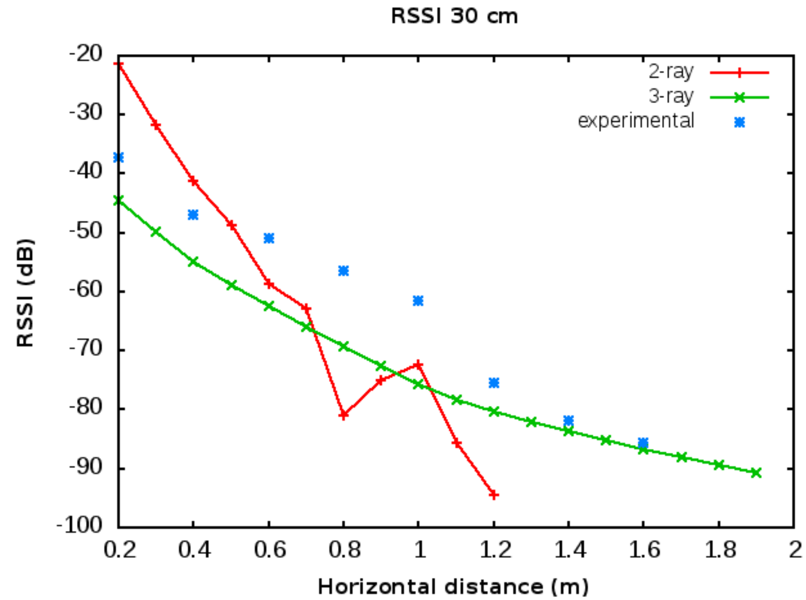
- Performance metrics
  - RSSI
  - Throughput
  - Packet Loss Ratio (PLR)
  - Delay
  - Delay Jitter

- Measured using
  ns-3 Flow monitor



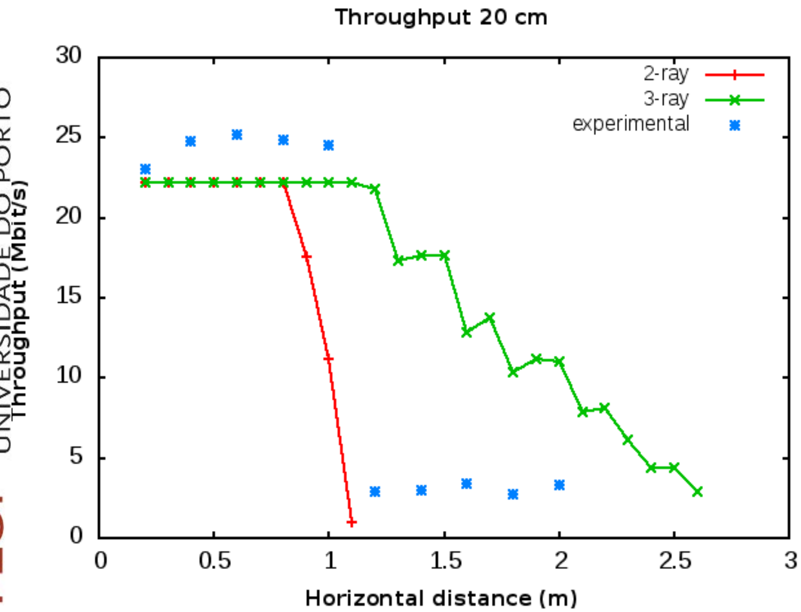
Simulation results - U2U, 2.4 GHz, RSSi

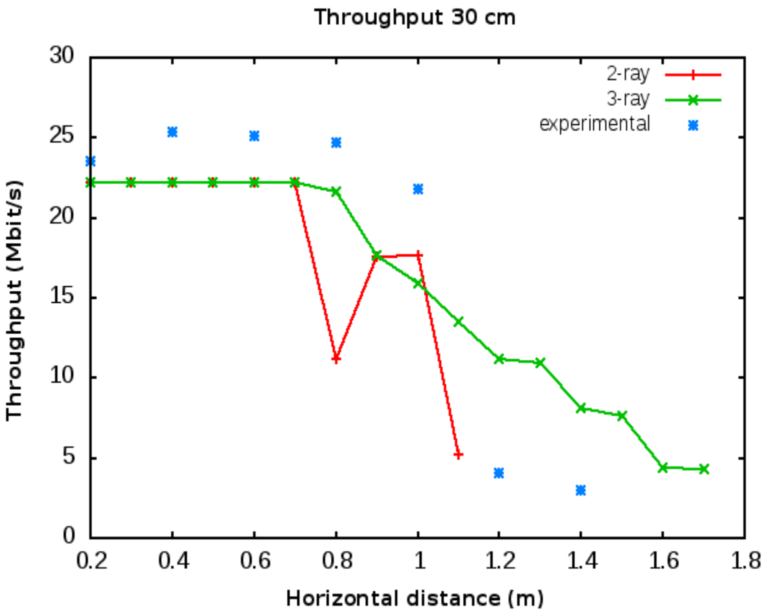




- RSSi difference 2 ray: 11 dBm @ 20 cm | 14 dBm @ 30 cm
- RSSi difference 3 ray: 5 dBm @ 20 cm | 8 dBm @ 30 cm
- Distance difference 3 ray: 21% @ 20 cm | 21% @ 30 cm
- 2-ray model not adequate for high horizontal distances
  - Lateral wave is the dominant component (d > 1m)
  - 3 ray model should be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

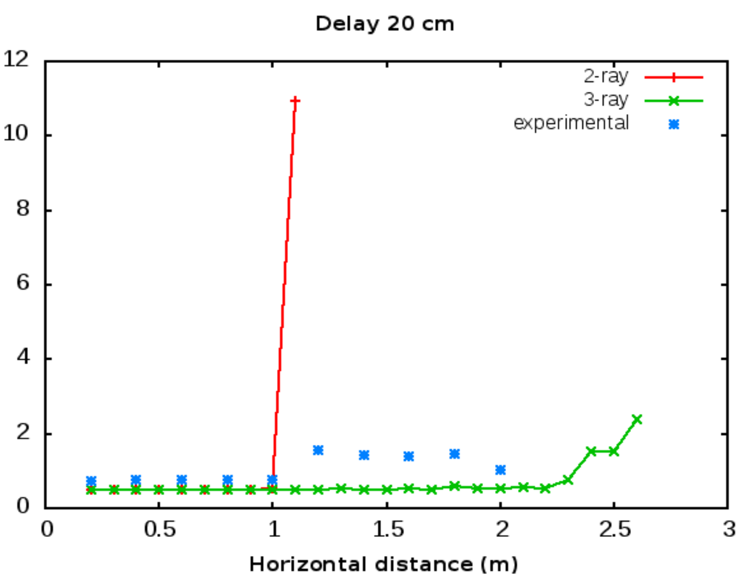
Simulation results - U2U, 2.4 GHz, Throughput

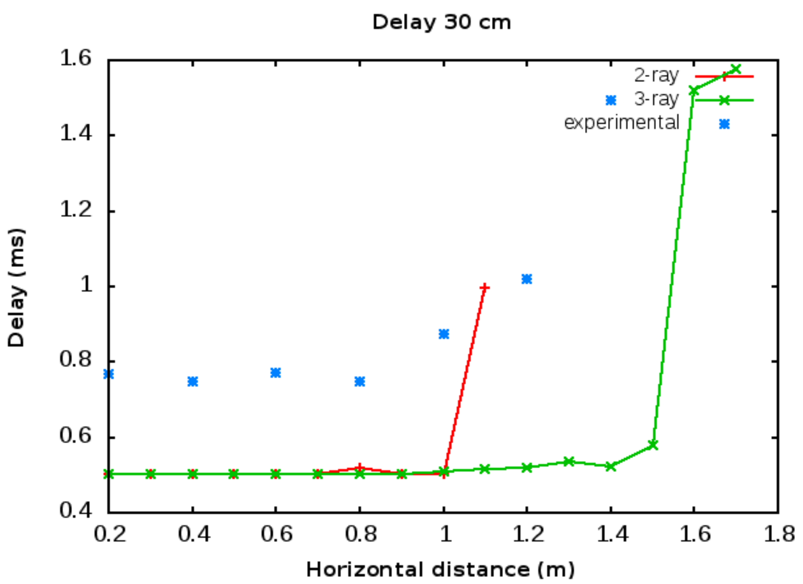




- Difference 2 ray: 4.5 Mbit/s @ 20 cm | 5 Mbit/s @ 30 cm
- Difference 3 ray: 7 Mbit/s @ 20 cm | 4 Mbit/s @ 30 cm
- Higher precision for high depths
- 2 ray model with results only until 1.1 m

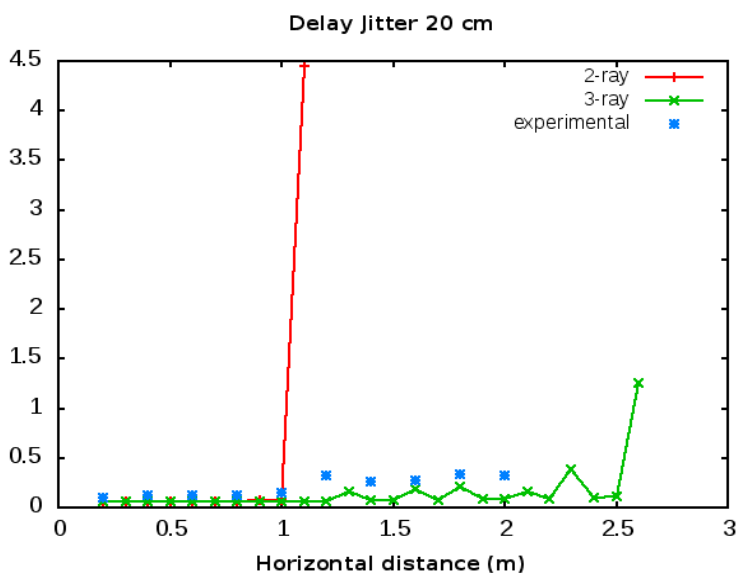
Simulation results - U2U, 2.4 GHz, Delay

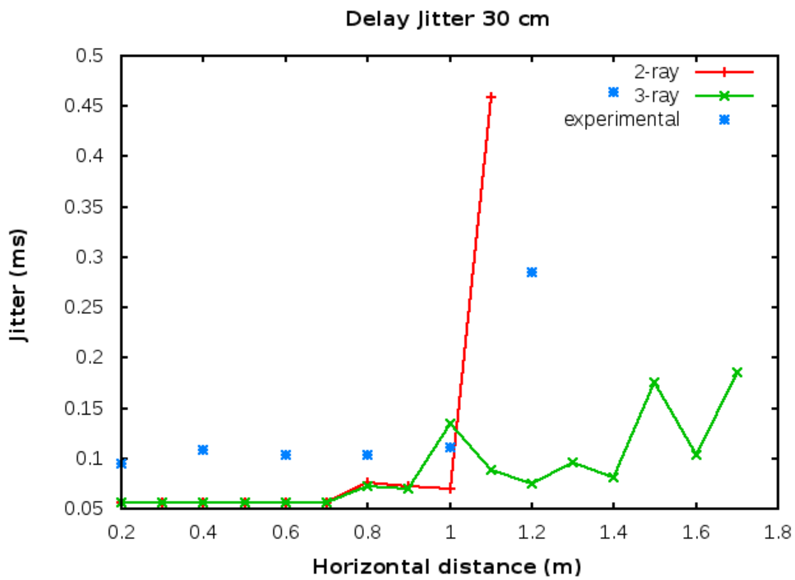




- Experimental results with ping – Round-trip time (RTT)
- Simulation results measure packet delay

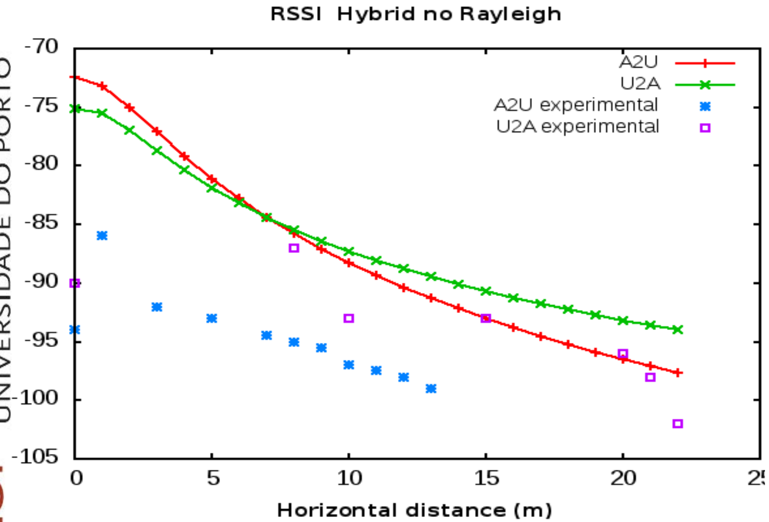
Simulation results - U2U, 2.4 GHz, Jitter

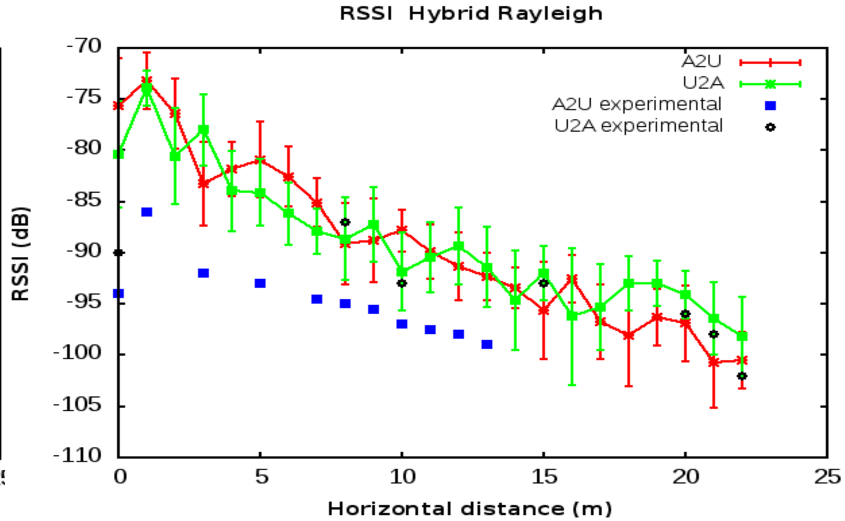




- Difference 2 ray: 0.06 ms @ 20 cm | 0.04 ms @ 30 cm
- Difference 3 ray: 0.12 ms @ 20 cm | 0.11 ms @ 30 cm
- Higher precision for high depths
- 2 ray model with results only until 1.1 m

Simulation results - U2A, A2U, 433 MHz

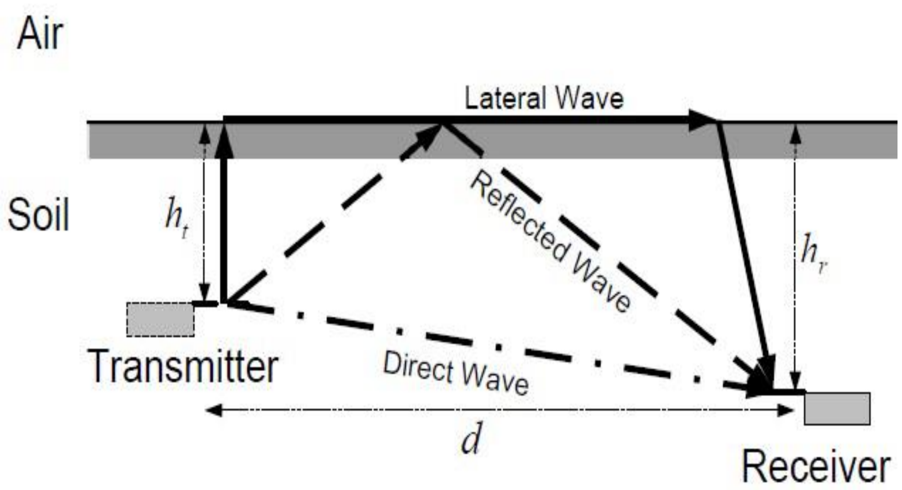




- Air node at 2.5 m height | Underground node at 35 cm
- No Rayleigh: RSSi difference: 4 dBm @ U2A | 10 dBm @ A2U
- Rayleigh: RSSi difference: 3 dBm @ U2A | 9.5 dBm @ A2U
- Multi path component introduces channel variability

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!