Implementation of a Channel Model for Non-Terrestrial Networks in ns-3

Mattia Sandri, Matteo Pagin, Marco Giordani, and Michele Zorzi
Department of Information Engineering, University of Padova, Italy
Outline

- Non-Terrestrial Networks
- ns-3 implementation
- Results and performance evaluation
- Conclusions and future work
Non-Terrestrial Networks (NTNs)

- In 2018, 55% of the global population lived in urban areas.
- 67% of the world’s population had a mobile subscription, but...
- ...only 3.9 billion people used the Internet $\rightarrow$ 3.7 billion people unconnected [1]!

U.S. LTE coverage (~areas where users can expect 5 Mbps DL, 1 Mbps UL) of AT&T, T-Mobile, UScellular, and Verizon, Source: FCC
Non-Terrestrial Networks (NTNs)

- NTNs ~ use of aerial vehicles and satellites to provide cellular coverage.
- Comprises:
  - Satellites (focus of this work)...
  - ...and also High Altitude Platform Stations (HAPS) and
  - Unmanned Aerial Vehicles (UAV).
- Satellites have been used in the past to offer services such as phone, television broadcasting.
- In the early 2010s the cost of satellite deployments has decreased, enabling a new set of satellite-offered services and giving rise to a renewed research interest.
Non-Terrestrial Networks (NTNs)

Satellite orbits:

- **Geostationary Equatorial Orbit (GEO)**
  - Rotates synchronously with the Earth.
  - Vast coverage area on the ground.
  - Long propagation distances.

- **Medium Earth Orbit (MEO)**

- **Low Earth Orbit (LEO)**
  - Shorter propagation distances.
  - Orbits around the Earth multiple times per day.
  - Relatively small coverage area on the ground.
State of the art and contributions

● NTNs are considered one of the key technology enablers for 6G...

● ...however, most NTN simulators, e.g., 5G K-Simulator, 5GVienna, and Simu5G, are proprietary, and/or require some type of commercial license to be used.

● Open-source options exist, but they tend to sacrifice higher layers accuracy for the sake of reducing computational complexity, e.g., 5G-air-simulator.

● → this work aims at filling these gaps, implementing in ns-3 the 3GPP TR 38.811 channel model → paving the way towards a 5G NR/6G NTN simulator.
Channel model implementation

- **The baseline model is the 3GPP TR 38.901**, implemented in [1] and which the 3GPP TR 38.811 [6] extends to model non-terrestrial wireless links.

- Notably, TR 38.811 considers also:
  - The impact of longer propagation distances (modified doppler shift, non-negligible propagation delay).
  - Atmospheric absorption, ionospheric and tropospheric scintillation.

- Our implementation extends [1] by both modifying the existing code and creating new classes.
NTN Channel Model Implementation

- A new mobility model, i.e., \texttt{GeocentricConstantPositionMobilityModel}:
  - Accounts for the Earth spherical shape and the satellite orbits.
  - Estimate and accounts for the elevation angle.
  - Supports Earth Centered Earth Fixed (ECEF) and geographic coordinates, and provide conversion methods between them.
  - Compatible with the ns-3 planar Cartesian coordinates, i.e., conversion to/from the former to achieve compatibility with the rest of the existing code.
NTN Channel Model Implementation

- A new antenna model, i.e., \texttt{CircularApertureAntennaModel}
  - Antenna field pattern based on the Bessel function of the first kind.
  - Conversely from the currently implemented models (\texttt{CosineAntennaModel}, \texttt{ParabolicAntennaModel}), \texttt{CircularApertureAntennaModel} implements the exact pattern with no approximations.
  - Leverages the efficient Bessel functions implementation introduced with C++17.
Additions:

- **Atmospheric absorption**
  - Based on the International Telecommunication Union (ITU) model P.676 [2].
  - Relevant for frequencies above 10 GHz, or when dealing with small elevation angles (< 10°).

- **Scintillation**
  - Ionospheric scintillation: based on the Gigahertz scintillation model from ITU model P.531 [3]. Relevant only for frequencies < 6 GHZ.
  - Tropospheric scintillation: non-negligible only for frequencies > 6 GHz, and based on data given in ITU model P.618 [4].
NTN Channel Model Implementation

Class: ThreeGppPropagationLossModel

- Support for all NTN propagation scenarios: Dense Urban, Urban, Suburban and Rural.
- Path loss modeling for NTN scenarios.
- Shadow fading and clutter loss parameters for NTN scenarios.

Class: ThreeGppChannelModel

- Support for all NTN propagation scenarios.
- Support for NTN-small scale fading, via the corresponding 3GPP parameters tables [6].
  - Each parameter depends on: frequency band, scenario, line of sight conditions, and elevation angle.
Simulation setup

- First, we perform link-level simulations to validate our implementation.
- We deploy two nodes:
  - “UE” on the ground.
  - “gNB” in orbit.
- We inspect the SNR, by computing the PSD of the received signal after the channel between the nodes.
- We average over 100 channel realizations to account for the statistical nature of the channel.

<table>
<thead>
<tr>
<th></th>
<th>Ground</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennas</td>
<td>Uniform Planar Array (UPA) - Circular Aperture</td>
<td>Circular Aperture</td>
</tr>
<tr>
<td>TX power, gain, noise figure</td>
<td>Set according to Table 6.1.1.1-1 [5]</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>S band (2 GHz) - Ka band (20 - 30 GHz)</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>400 KHz</td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>1 m</td>
<td>600 km (LEO) 1200 km (LEO) 35786 km (GEO)</td>
</tr>
<tr>
<td>Simulation duration</td>
<td>1 s</td>
<td></td>
</tr>
</tbody>
</table>
We first calibrate our implementation, by comparing link-level results with the reference ones provided by 3GPP in Tab. 6.1.3.3-1, TR 38.811 [5].

We consider eight of the scenarios outlined by 3GPP in [5], which comprise all types of orbits and frequency bands combinations.

The obtained average SNR values deviate at most of 0.4 dB from the reference ones, thus validating our implementation.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>DL</td>
<td>3GPP</td>
<td>210.6</td>
<td>1.2</td>
<td>1.1</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Obtained</td>
<td>210.6</td>
<td>1.4</td>
<td>1.1</td>
<td>11.3</td>
</tr>
<tr>
<td>1</td>
<td>UL</td>
<td>3GPP</td>
<td>214.1</td>
<td>1.1</td>
<td>1.1</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Obtained</td>
<td>214.2</td>
<td>1.4</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>DL</td>
<td>3GPP</td>
<td>179.1</td>
<td>0.5</td>
<td>0.3</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Obtained</td>
<td>179.9</td>
<td>0.5</td>
<td>0.3</td>
<td>8.6</td>
</tr>
<tr>
<td>6</td>
<td>UL</td>
<td>3GPP</td>
<td>182.6</td>
<td>0.5</td>
<td>0.3</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Obtained</td>
<td>182.6</td>
<td>0.5</td>
<td>0.3</td>
<td>18.4</td>
</tr>
<tr>
<td>9</td>
<td>DL</td>
<td>3GPP</td>
<td>159.1</td>
<td>0.1</td>
<td>2.2</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Obtained</td>
<td>159.1</td>
<td>0.0</td>
<td>2.2</td>
<td>6.7</td>
</tr>
<tr>
<td>9</td>
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<td>3GPP</td>
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<td>0.1</td>
<td>2.2</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>159.1</td>
<td>0.0</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>14</td>
<td>DL</td>
<td>3GPP</td>
<td>164.5</td>
<td>0.1</td>
<td>2.2</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Obtained</td>
<td>164.5</td>
<td>0.0</td>
<td>2.2</td>
<td>7.3</td>
</tr>
<tr>
<td>14</td>
<td>UL</td>
<td>3GPP</td>
<td>164.5</td>
<td>0.1</td>
<td>2.2</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Obtained</td>
<td>164.5</td>
<td>0.0</td>
<td>2.2</td>
<td>-3</td>
</tr>
</tbody>
</table>
Then, we analyze the impact of the carrier frequency (0.5 GHz - 100 GHz) on the SNR.

We deploy a GEO satellite, transmitting a downlink signal towards a parabolic antenna on the ground.

- The TX power is 37.5 dBm, with a 90° elevation angle.

- Attenuation peak ~60 GHz caused by oxygen absorption.

![SNR vs Frequency Graph]
Link-level simulations

- We complete our link-level analysis by performing a mobility test.
- We deploy a satellite which transmits downlink signals towards a parabolic antenna on the ground.
  - The TX power is 37.5 dBm.
  - Satellite varies its altitude in [300, 1600] km (top) and its longitude in [8.8, 14.8]° (bottom).
  - In the longitude test, the receiver is perpendicular to the satellite at 11.8°, while the elevation angle is fixed to 90° for the altitude test.
End-to-end simulations

- Preliminary 5G NR end-to-end simulations using the mmWave module [7].
- Satellite gNB exchanges 10 Mbps constant bitrate UDP application data with a UE on the ground.

<table>
<thead>
<tr>
<th>Scenario:</th>
<th>1 GEO</th>
<th>6 LEO600</th>
<th>9 LEO600</th>
<th>14 LEO1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx Power:</td>
<td>37.52 dBm</td>
<td>21.52 dBm</td>
<td>48.77 dBm</td>
<td>54.77 dBm</td>
</tr>
<tr>
<td>Drop ratio</td>
<td>0.61</td>
<td>0.67</td>
<td>0.45</td>
<td>0.36</td>
</tr>
<tr>
<td>Frequency band:</td>
<td>Ka-band</td>
<td>Ka-band</td>
<td>S-band</td>
<td>S-band</td>
</tr>
<tr>
<td>UE terminal:</td>
<td>VSAT</td>
<td>VSAT</td>
<td>Handheld</td>
<td>Handheld</td>
</tr>
</tbody>
</table>

Comparison between 4 of the scenarios (1, 6, 9, 14) outlined by 3GPP in Sec. 6, TR 38.821 [5].

- Increasing satellite altitude 600 km → 1200 km requires an increase in the TX power 75 W → 300 W.
- Up to 67% packet loss in Scenario 6.
- Communication is possible even with a GEO orbit, from an SNR standpoint... however, one-way propagation delay > 119.2 ms!
Conclusions and future work

TLDR:

- We implemented the TR 38.811 channel model in ns-3, extending the mainline ns-3, and thus enabling full stack end-to-end performance evaluation of NTN scenarios.
- We calibrated our implementation using 3GPP reference values.

As part of our future work, we plan to:

- Account for the non-negligible propagation delay.
- Extend proposed mobility model with the support for realistic orbits.
- Support more complex simulations, such as:
  - Simulations with moving UEs and satellites.
  - HAP and UAV scenarios.
Thank you for your attention.

Questions, suggestions...?
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Backup slides
Link-level simulations

- The use of handheld devices limits UL capabilities.
- High TX power (75W) required for DL.

- More energy efficient thanks to the use of VSAT antennas.
- SNR > 0dB in UL.

S-band 2 GHz  BW: 30MHz  UE antenna: UPA 2x2

Ka-band 20-30 GHz  BW: 40MHz  UE terminal: VSAT 39.7 dB
References


[6] 3GPP TR 38.821: Solutions for NR to support Non-Terrestrial Networks (NTN)

[7] 3GPP TR 38.811: Study on New Radio (NR) to support non-terrestrial networks

[8] M. Mezzavilla et al., "End-to-End Simulation of 5G mmWave Networks"
NTN: Channel Model Implementation

- **Bold**: newly implemented code
- **Dotted**: modifications to the existing code

Channel model:
- Scintillation
  - Atmospheric Absorption
  - Shadowing
  - Pathloss

Auxiliary models:
- Circular Aperture Antenna
- Mobility Model
- Channel Condition Model