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SIGNET

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Improving the Efficiency of MIMO Simulations in ns-3

Matteo Pagin^, Sandra Lagén*, Biljana Bojović*, Michele Polese°, Michele Zorzi^

^Department of Information Engineering, University of Padova

*Centre Tecnològic de Telecomunicacions de Catalunya

°Institute for the Wireless Internet of Things, Northeastern University

paginmatte@dei.unipd.it

Outline

- **Introduction**
- **Codebase optimizations**
- **Design level optimizations**
- **Results**
- **Conclusions and future work**

Introduction | Role of system-level simulators

- **Availability of SDR-based experimental platforms, such as those of Platform for Advanced Wireless Research (PAWR)**

- **System-level simulators still represent a viable performance evaluation tool:**
  - They can model large-scale deployments.
  - Easier to develop and prototype solutions, no hard hardware limitations.
- **However, they must provide:**
  - **Good trade-off between fidelity and computational efficiency.**
  - **Stability and ease of implementation/prototype development.**

Introduction | Channel modeling

- **Channel modeling is a fundamental component of any wireless communication simulator.**

- **Analytical models (Nakagami-m, Rayleigh, Rician) → too simplistic**
- **Ray-tracers → accurate,** but require detailed representation of the environment, and **computationally intensive.**
- **Hybrid statistical channel models → deterministic components (Path loss) and random ones (Fading)**
    - **3GPP TR 38.901 (0.5-100 GHz) →** MIMO simulations, **up to 90% of simulation time for channel matrix and beamforming gain [1]**

Codebase optimizations | Channel matrix generation

- We observed that **part of the TR 38.901 channel matrix generation computations were unnecessarily repeated for each element of the channel matrix**
  - → significant overhead, as trigonometric evaluations are computationally intensive.
  - Trigonometric evaluations $O(\text{UxSxN}) \rightarrow O(\text{N})$, where U and S = number of transmitting and receiving antenna elements, N = number of multipath signal clusters.

Codebase optimizations | Eigen

- **Improved the algebra manipulations of the channel matrix performed in ThreeGppSPLM by introducing the support for the open-source library Eigen.**
- Eigen is a linear algebra C++ template library that offers fast routines for algebra primitives [2].
- Set as an **optional, external ns-3 dependency**, with the goal of minimizing future code maintenance efforts.
- Developed a set of common API to make remainder of the code abstracted with respect to the possible presence of Eigen in the host system.

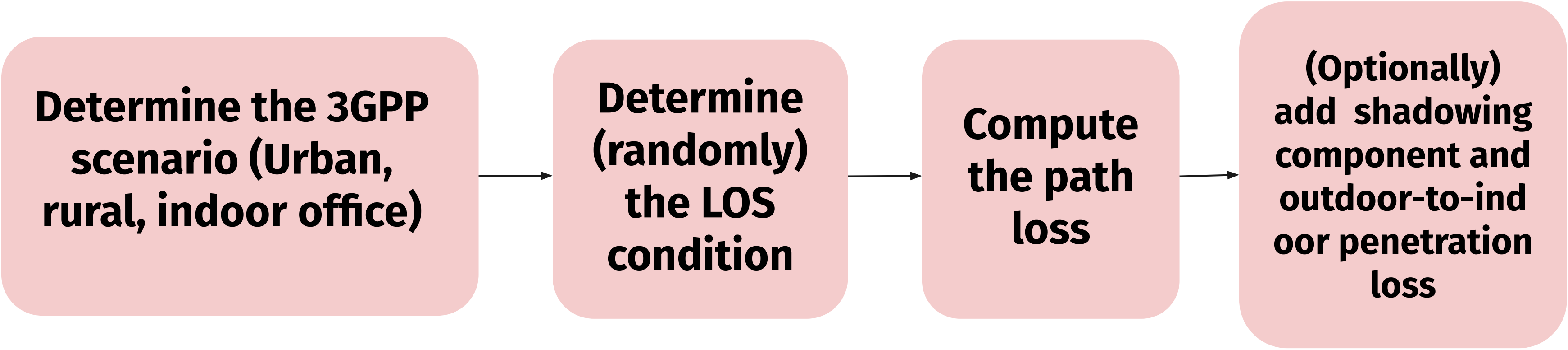
Design-level optimizations | TwoRaySPLM

- Auxiliary model which aims to offer a **faster, albeit slightly less accurate, statistical channel model than 3GPP TR 38.901.**
- **Frequency range of applicability of this model is 0.5 – 100 GHz…**
  - …and easy to extend to higher frequencies.
- The **channel gain is computed by combining several scalar loss and gain terms** (large- and small-scale propagation phenomena, antenna and beamforming gains)

$$\mathrm{P}_R^x[dBm] = \mathrm{P}_T^x[dBm] - \mathrm{PL}_{T,R}[dB] + \mathrm{S}_{T,R}[dB] + G_{T,R}[dB] + F_{T,R}[dB]$$

Design-level optimizations | Large-scale phenomena

- **Large-scale propagation phenomena use the 3GPP TR 38.901 model [3], since its implementation [4] is not computationally demanding.**



Design-level optimizations | Array and beamforming gain

- The **combined array and beamforming gain** is computed as:

$$G_{T,R}(\theta,\varphi) = G_{T,R}^{iso}(\theta,\varphi)\,|g(\theta,\varphi)|^2$$

- where:

$$G_{T,R}^{iso}(\theta,\varphi) = \left|\boldsymbol{a}_{\boldsymbol{i}}^{\mathrm{T}}(\theta,\varphi)\boldsymbol{w}\left(\theta_0,\varphi_0\right)\right|^2$$

Support for arbitrary antenna patterns.

- ~ abstracting the channel as a SISO keyhole [5]. For NLoS links no dominant component→ multiplicative correction factor η which scales the beamforming gain.

Design-level optimizations | Small scale fading

- Rayleigh and Rician distributions fail to capture the intrinsic bimodality exhibited by mmWaves [6].
- **We model fast fading using the more general Fluctuating Two-Ray (FTR) model** [7]
  - Two dominant specular components.
  - A mixture of scattered paths.

$$V_r = V_1\sqrt{\xi}\exp(j\phi_1) + V_2\sqrt{\xi}\exp(j\phi_2) + X + jY$$

ϕ_1, ϕ_2: ~ $U\,[0, 2\pi]$

ξ: unit-mean Gamma

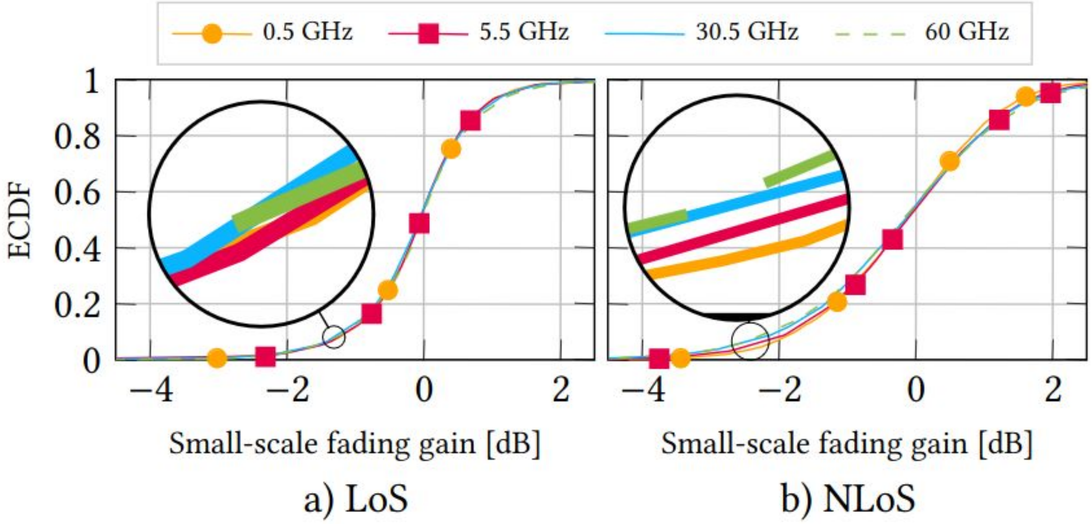
X, Y: ~ $N\,(0, \sigma^2)$

Design-level optimizations | Calibration

- **How to choose the FTR model parameters?**
- Simulation script which produces **channel gain samples obtained using the fully-fledged 3GPP TR 38.901 model.**
    - Neglect beamforming gain, path-loss, shadowing and blockages → **isolate the small-scale fading**.
- Separate set of samples for different:
    - LoS conditions.
    - 3GPP propagation scenarios.
    - Set of carrier frequencies in [0.5, 100] GHz.

Design-level optimizations | Calibration

- **No significant dependency on the carrier frequency → discarded this parameter from the calibration grid.**



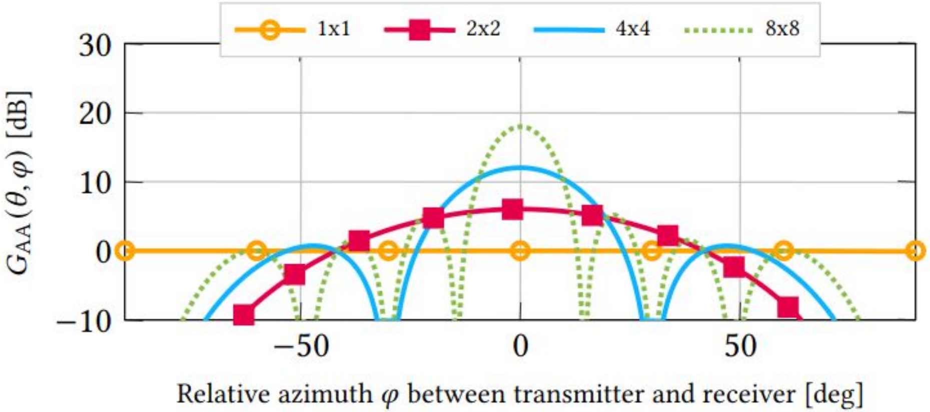
Small-scale fading gain statistics for the UMi propagation scenario versus the carrier frequency f_C, for both LoS and NLoS channel conditions.

Design-level optimizations | Calibration

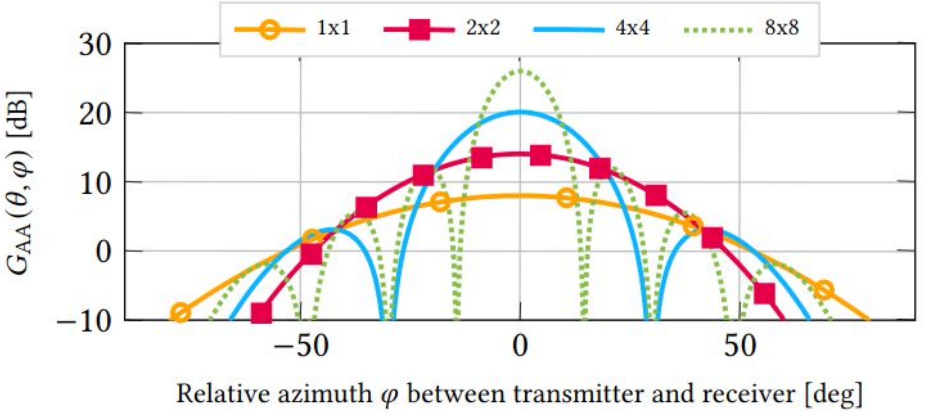
- Then, we used the **reference fading statistics to find and cache the best matching FTR distribution**.
- For each pair of channel conditions and propagation scenarios:

1. **Generate a discrete grid of FTR model parameters spanning their whole domain** →
2. **Sample fading realizations for each parameter combination** →
3. **Compute the distance between the corresponding ECDF and the reference one** (← Anderson-Darling goodness-of-fit measure) →
4. **Pick and store the parameters yielding smallest distance between the distributions**

Results | Array gain

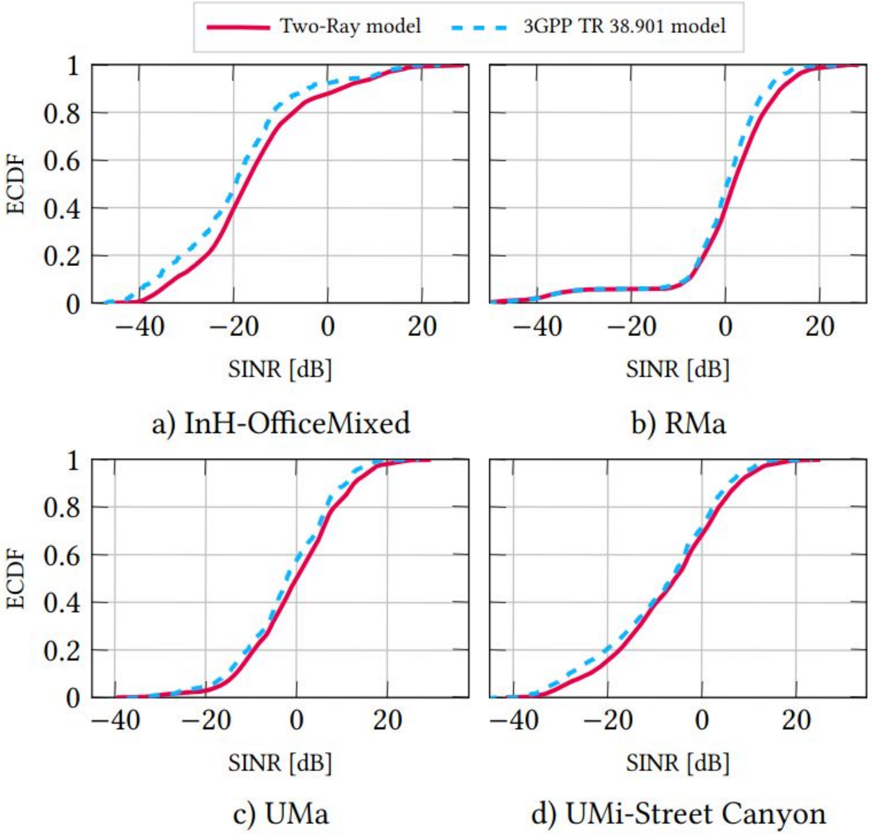


Isotropic radiating elements



Directional antenna radiation pattern [3, Sec. 7.3]

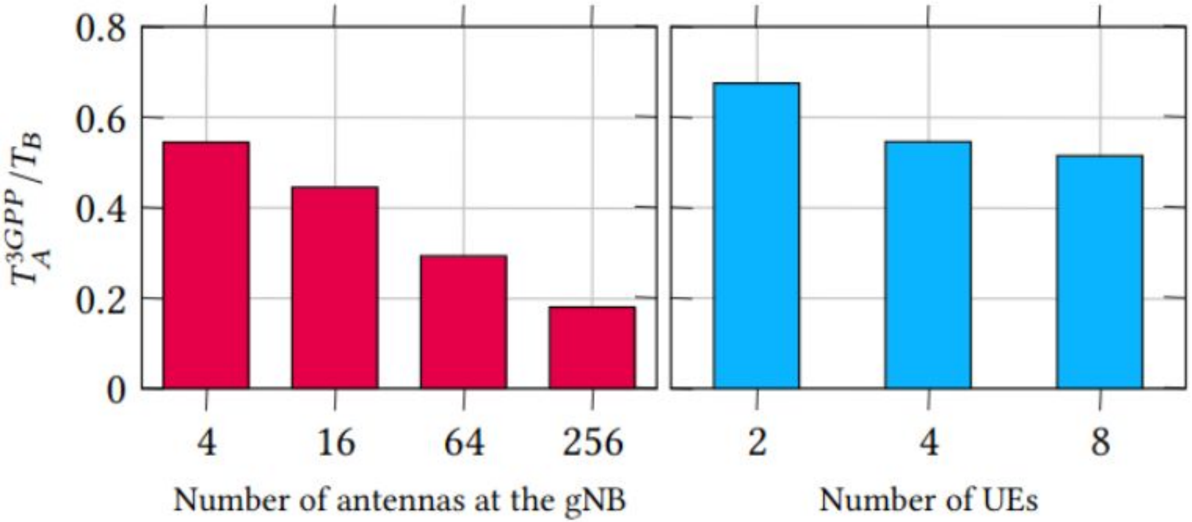
Results | SNR statistics



SINR statistics comparison of the performance-oriented channel model, versus the fully-fledged 3GPP TR 38.901.

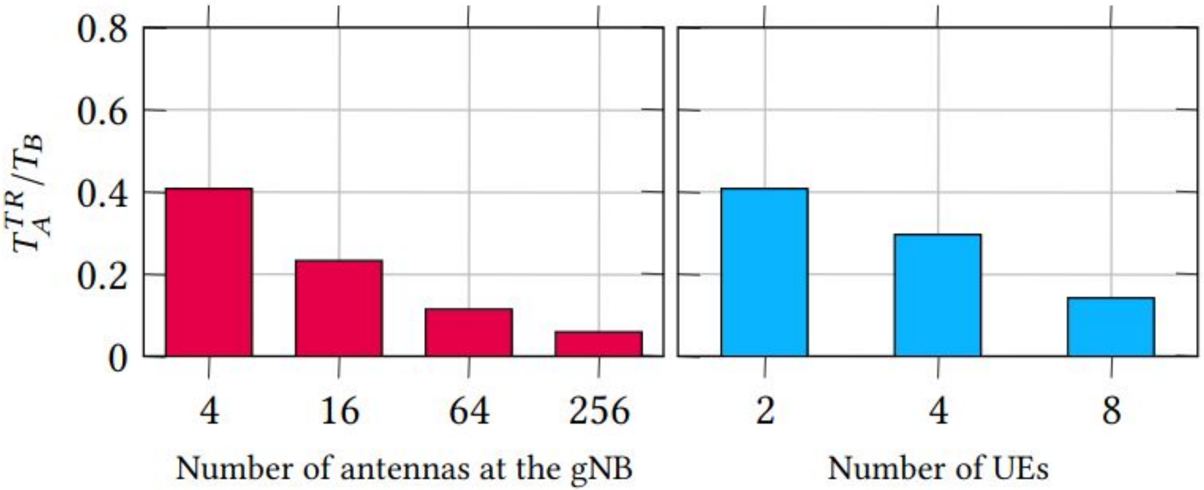
We consider four different 3GPP propagations scenarios (InH-Office Mixed, RMa, UMa and UMi-Street Canyon).

Results | Simulation times codebase optimizations



Ratio of the median simulation times after the merge of this work, and thus with Eigen’s integration) and the 3GPP TR 38.901 model.

Results | Simulation times design-level optimizations



Ratio of the median simulation times using the performance-oriented channel model presented in this work and the 3GPP TR 38.901 model. In this case, Eigen is disabled.

Conclusions

- **We introduced a set of optimizations concerning the simulation of MIMO wireless channels in ns-3:**
  - Support for the linear algebra library Eigen in ns-3
  - Reduced the computational complexity of the channel matrix generation procedure by avoiding the unnecessary repetition of trigonometric evaluations.
  - Designed and implemented in ns-3 a performance-oriented statistical channel model based on the FTR fading model.
- **→ up to 80% reduction in the simulation time with the fully-fledged TR 38.901 model, and further reduction with the performance-oriented model.**

Future work

- **Possible extensions of this analysis include:**
  - Refined beamforming gain correction factors.
  - More efficient storage/access data structures and linear algebra operations for 3D matrices.
  - Single instruction, multiple data (SIMD) for speeding up the evaluation of trigonometric functions.
  - Caching the beamforming gain and the fading realization in the performance-oriented model.

References

[1] . Paolo Testolina, Mattia Lecci, Michele Polese, Marco Giordani, and Michele Zorzi. 2020. Scalable and Accurate Modeling of the Millimeter Wave Channel. In International Conference on Computing, Networking and Communications (ICNC). IEEE, Big Island, Hawaii, USA

[2] . Gaël Guennebaud, Benoît Jacob, et al. 2010. Eigen v3. http://eigen.tuxfamily.org

[3] . 3GPP. 2019. Study on Channel Model for Frequencies from 0.5 to 100 GHz. TR 38.901 (Rel. 15), V15.0.0

[4] . Tommaso Zugno, Michele Polese, Natale Patriciello, Biljana Bojović, Sandra Lagén, and Michele Zorzi. 2020. Implementation of a Spatial Channel Model for ns-3. In Proceedings of the 2020 Workshop on ns-3. Association for Computing Machinery, Gaithersburg, MD, USA

[5] . Dmitry Chizhik, Gerald J. Foschini, and Reinaldo A. Valenzuela. 2000. Capacities of Multi-element Transmit and Receive Antennas: Correlations and Keyholes. Electronics Letters 36, 13 (Jun. 2000), 1

[6] . Theodoros Mavridis, Luca Petrillo, Julien Sarrazin, Aziz Benlarbi-Delai, and Philippe De Doncker. 2015. Near-Body Shadowing Analysis at 60 GHz. IEEE Transactions on Antennas and Propagation 63, 10 (Jul. 2015), 4505–4511

[7] . Juan M. Romero-Jerez, F. Javier Lopez-Martinez, José F. Paris, and Andrea J. Goldsmith. 2017. The Fluctuating Two-Ray Fading Model: Statistical Characterization and Performance Analysis. IEEE Transactions on Wireless Communications 16, 7 (May 2017), 4420–4432

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Introduction | Towards future cellular networks

- **6G cellular networks are poised to:**
  - Further expand the spectrum towards the **THz** band.
  - Shift towards an **Artificial Intelligence (AI)-native network design** → autonomous orchestration of the network.
  - Provide **ubiquitous connectivity to both people and machines.**