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TOWARDS SUSTAINABLE MOBILE NETWORKS: EVALUATING PROPAGATION MODELS FOR ENERGY-EFFICIENT 5G AND BEYOND

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The rapid rollout of 5G and beyond mobile networks has resulted in denser infrastructure deployments and increased use of mid-microwave frequency bands such as 3.6 GHz and 6 GHz. While these developments improve capacity and spectrum efficiency, they also raise energy consumption during both network operation and planning. Radio wave propagation models play a key role in this context, as their accuracy, terrain awareness, and computational efficiency directly affect the number of required simulations, field measurements, and planning iterations. This paper evaluates empirical, hybrid, and deterministic propagation models from a sustainability-oriented perspective. Using urban, flat rural, and hilly Hungarian terrains as representative environments, the performance of ITU-R P.1546-6, the SUI model, ITU-R P.452-17, and the Parabolic Equation Method is assessed at 3.6 GHz and 6 GHz. The results show that terrain-aware and computationally efficient models can significantly reduce planning-related energy consumption while maintaining acceptable prediction accuracy, supporting greener mobile network design.

1. Introduction

The evolution of mobile communication systems towards 5G and beyond has fundamentally altered network design principles. Higher carrier frequencies, denser base station deployments, and increased spatial reuse enable high data rates and low latency but also lead to rising energy demand. This increase is not limited to network operation; planning and optimization processes themselves require extensive simulations and repeated evaluations, contributing to the overall environmental footprint of mobile networks.

As conceptually illustrated in Figure 1, the evolution towards dense 5G and beyond networks requires propagation modelling approaches that jointly address prediction accuracy, terrain sensitivity, and sustainability-related constraints.

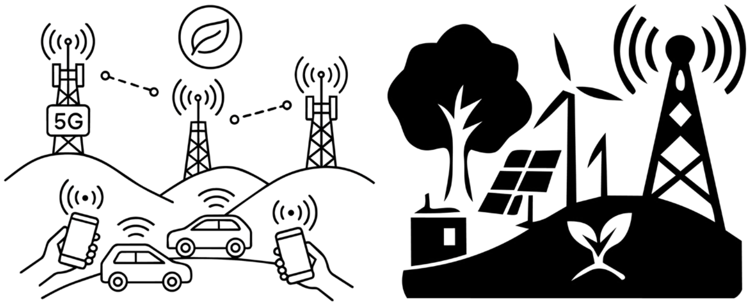


Figure 1: Conceptual illustration of sustainable 5G and beyond mobile networks: (a) dense 5G connectivity supporting mobile and vehicular users under sustainability constraints; (b) integration of wireless infrastructure with renewable energy and natural environment.

Sustainability in mobile communications extends beyond hardware efficiency and transmission power control. Propagation modelling plays a central role in network planning, as inaccurate or poorly chosen models can lead to unnecessary simulations, repeated parameter tuning, and costly field measurement campaigns. Conversely, accurate and computationally efficient models reduce planning effort and associated energy consumption (An et al., 2024).
Previous comparative studies have shown that propagation model accuracy and terrain sensitivity depend strongly on frequency band and environmental conditions, particularly at 3.6 GHz and 6 GHz. However, the implications of these differences for sustainable and energy-efficient network planning are often addressed only implicitly. This paper interprets propagation model performance explicitly through a sustainability lens, focusing on the trade-off between accuracy, terrain awareness, and computational complexity.

2. Propagation modelling background and sustainability aspects

Radio wave propagation models can be interpreted as systems that transform transmitter-related parameters and environmental descriptors into predicted path loss or electric field strength values (Erceg et al., 2001). This system-level abstraction provides a unified framework for comparing different modelling approaches and for understanding how modelling choices influence both prediction accuracy and planning-related energy consumption. The general structure of a wave propagation model, including the relationship between environmental inputs and predicted field strength, is illustrated in Figure 2.

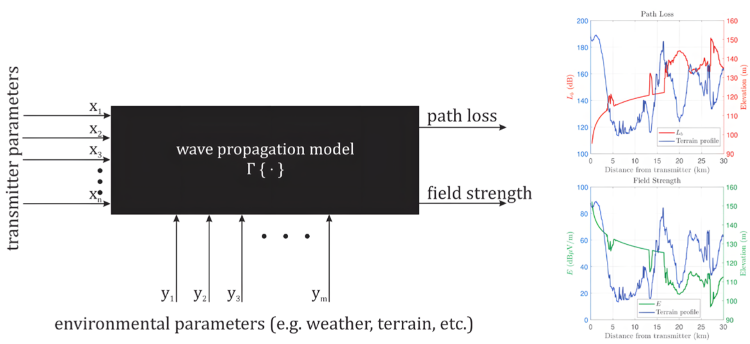


Figure 2: System model of a wave propagation model

Propagation models commonly used in mobile network planning can be grouped into three main categories. Empirical models are derived from measurement-based relationships and provide fast predictions, but their validity is often limited to specific environments. Deterministic models, such as the Parabolic Equation Method (PEM), are based on physical formulations of electromagnetic wave propagation and explicitly account for terrain-induced diffraction and refraction (Levy, 2000), offering high accuracy at the cost of substantial computational effort. The numerical solution of the parabolic equation relies on finite-difference schemes, such as the classical Crank–Nicolson method (Crank and Nicolson, 1947). Hybrid models combine empirical formulations with simplified physical mechanisms in order to balance accuracy and efficiency.

From a sustainability perspective, these differences translate into distinct planning-related energy footprints. Empirical models may require repeated simulations or corrections when applied to complex terrain, while deterministic models, although accurate, are computationally intensive. Hybrid, terrain-aware models represent a promising compromise for energy-efficient network planning.

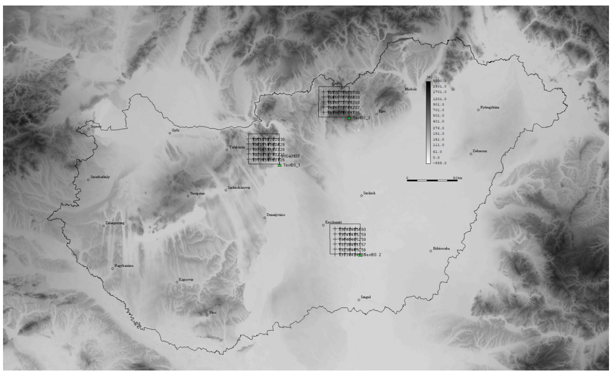
3. Considered models and evaluation framework

The analysis focuses on radio wave propagation models that are relevant for current and future mobile networks operating at 3.6 GHz and 6 GHz. At 3.6 GHz, the empirical ITU-R P.1546-6 model (ITU-R, 2019) and the hybrid ITU-R P.452-17 model (ITU-R, 2021) are evaluated against the deterministic Parabolic Equation Method (PEM) (Rasool et al., 2022), which serves as a high-accuracy reference. At 6 GHz, the performance of the SUI model and ITU-R P.452-17 is similarly assessed relative to PEM.

The classification of the investigated models according to their modelling approach and applicable frequency bands is summarized in Table 1 (Mollel and Kisangiri, 2014). The evaluation is carried out over three representative Hungarian environments in order to capture diverse terrain characteristics. These include an urban, moderately hilly area near Budapest; a flat rural region near Kecskemét; and a hilly, mountainous area around Kékestető. The geographic distribution of the considered test sites and the corresponding terrain profiles are illustrated in Figure 3.

Table 1: Classification of the considered propagation models

Model Type	3.6 GHz	6 GHz
Empirical	ITU-R P.1546	SUI Model
Deterministic	Parabolic Equation Modelling	
Hybrid	ITU-R P.452, ITU-R P.1812	ITU-R P.452



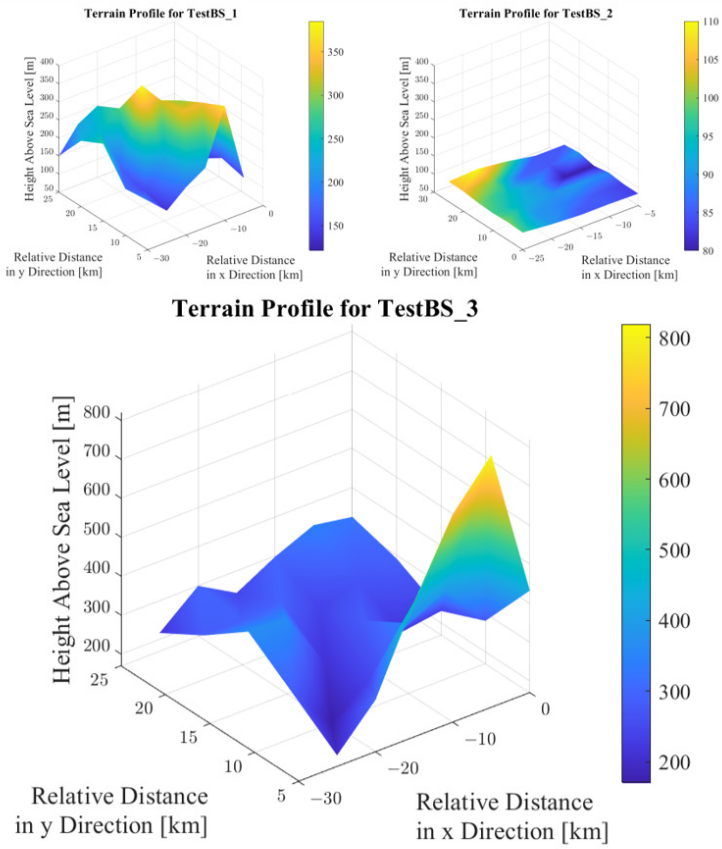


Figure 3: Considered test cases in Hungary and the terrain profiles of the three test sites

Model performance is assessed using standard statistical error metrics, including Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and bias, with PEM serving as the reference solution. In addition to absolute accuracy, terrain sensitivity is quantified by evaluating the Pearson correlation coefficient between the standard deviation of terrain elevation, denoted by σ_terrain, and the standard deviation of the predicted electric field strength values, σ_FST. This metric provides a compact measure of how strongly each model responds to variations in terrain complexity (Rappaport, 2001).
The relationship between the basic transmission loss and the resulting electric field strength is given by

$$E=EIRP-L+10\log_{10}(f)+79.35, \quad (1)$$

where E is the electric field strength in dBµV/m, ERP denotes the effective radiated power in dBm, L is the basic transmission loss in dB, and f is the operating frequency in MHz (Unger and Kuczmann, 2025a).

4. Results: accuracy and terrain sensitivity

4.1 Results at 3.6 GHz

At 3.6 GHz, pronounced differences are observed between the investigated propagation models when evaluated relative to the deterministic PEM reference. The empirical ITU-R P.1546-6 model exhibits weak or even negative terrain correlation in complex environments, which is reflected in high RMSE and MAE values, substantial bias, and large relative errors with respect to PEM, as summarized in Table 2. These results indicate that the empirical model struggles to capture terrain-dependent propagation effects at this frequency band.

Table 2: Error metrics at 3.6 GHz relative to PEM

		3.6 GHz			
Base Station	**Model**	**RMSE (dBµV/m)**	**MAE (dBµV/m)**	**Bias (dBµV/m)**	**RelErr (%)**
TestBS_1	P.1546-6	32.45	25.30	12.03	159.26
TestBS_1	P.452-17	27.80	20.22	13.02	148.24
TestBS_2	P.1546-6	28.51	27.71	-27.71	41.28
TestBS_2	P.452-17	6.49	5.57	-4.53	8.27
TestBS_3	P.1546-6	51.30	38.35	38.35	488.13
TestBS_3	P.452-17	20.50	11.15	4.59	112.82

In contrast, the hybrid ITU-R P.452-17 model demonstrates significantly improved performance. As shown in Table 2, lower error metrics and reduced bias are achieved in most test scenarios when compared to the PEM reference, particularly in flat and moderately hilly environments. This confirms that incorporating simplified physical mechanisms leads to more reliable predictions without the computational burden of fully deterministic methods.

The terrain sensitivity analysis further supports these observations. The correlation between terrain elevation variability and predicted field strength variation is markedly higher for ITU-R P.452-17 and PEM than for the empirical model, as quantified in Table 3. This confirms that explicit terrain awareness plays a key role in improving prediction reliability at 3.6 GHz. Differences in predicted field strength relative to PEM further highlight the improved terrain responsiveness of ITU-R P.452-17 compared to empirical approaches, as illustrated in Figure 4.

		3.6 GHz		
Model	**Base Station**	**σ_terrain (m)**	**σ_FST (dBµV/m)**	**Pearson r**
PEM	TestBS_1	71.54	39.81	0.8053
	TestBS_2	7.99	9.46	
	TestBS_3	139.91	36.81	
ITU-R P.1546-6	TestBS_1	71.54	14.60	-0.5545
	TestBS_2	7.99	11.29	
	TestBS_3	139.91	7.44	
ITU-R P.452-17	TestBS_1	71.54	21.30	0.9124
	TestBS_2	7.99	8.20	
	TestBS_3	139.91	23.31	

4.2 Results at 6 GHz

At 6 GHz, clear performance differences are observed between the investigated propagation models when evaluated relative to the deterministic PEM reference. The empirical SUI model exhibits higher prediction errors and systematic underestimation of the electric field strength across all investigated base stations, as summarized in Table 4.

Table 4: Combined accuracy and terrain sensitivity results at 6 GHz based on test-point evaluations, expressed by prediction error metrics and the relationship between terrain variability and field strength variation, relative to the PEM reference

6 GHz								
Base Station	Model	RMSE (dBμV/m)	MAE (dBμV/m)	Bias (dBμV/m)	RelErr (%)	σ_terrain (m)	σ_FST (dBμV/m)	Pearson r
TestBS_1	SUI	38.56	32.05	-4.45	97.49	71.54	44.56	0.3855
TestBS_1	ITU-R P.452-17	31.68	23.28	13.06	100.18	71.54	22.12	0.9134
TestBS_2	SUI	54.67	54.23	-54.23	82.53	7.99	11.68	0.3855
TestBS_2	ITU-R P.452-17	6.83	5.69	-2.26	8.64	7.99	7.73	0.9134
TestBS_3	SUI	47.52	40.43	-26.83	107.58	139.91	10.34	0.3855
TestBS_3	ITU-R P.452-17	25.49	14.98	3.04	72.51	139.91	24.39	0.9134

In contrast, the hybrid ITU-R P.452-17 model achieves consistently lower error metrics and reduced bias with respect to PEM. In addition, the combined results in Table 4 indicate that ITU-R P.452-17 preserves a stronger and more consistent relationship between terrain variability and predicted field strength variation than the empirical model.
Overall, the results reported in Table 4 confirm that, at 6 GHz, terrain-aware hybrid modeling provides a more reliable and robust solution than purely empirical approaches.

5. Sustainability perspective: accuracy-complexity trade-off at 3.6 GHz

The results obtained at 3.6 GHz highlight that propagation model selection has a direct impact on both prediction reliability and the sustainability of network planning processes. Models with limited terrain sensitivity tend to produce biased or unstable predictions as terrain resolution changes, which often necessitates repeated simulations, recalibration, or additional field measurements. These iterative planning steps increase computational load and associated energy consumption.
Deterministic approaches such as the Parabolic Equation Method (PEM) provide physically accurate reference results and exhibit a strong and consistent response to changes in terrain resolution. However, their computational complexity limits their applicability in large-scale or iterative planning tasks. In contrast, hybrid models, particularly ITU-R P.452-17, preserve a terrain-dependent behaviour that closely follows the deterministic reference while significantly reducing computational requirements.
The influence of terrain resolution on prediction accuracy at 3.6 GHz is illustrated in Figure 5, which presents the variation of multiple error metrics–including RMSE, MAE, bias, relative error, and normalized RMSE–as a function of raster resolution for urban, flat, and mountainous environments. The figure shows that hybrid and deterministic models maintain a more stable accuracy profile across increasing terrain resolutions, whereas empirical models exhibit a pronounced degradation, especially in complex terrain.
To further quantify terrain-induced propagation complexity, terrain profiles can be analysed in the spectral domain. The Spectral Complexity Ratio (SCR) is defined as

$$R^{(k)} = \frac{HFE}{LFE + HFE} \qquad (2)$$

where HFE and LFE denote the high- and low-frequency spectral energy components of the terrain profile. The SCR provides a compact indicator of terrain complexity and supports adaptive modeling strategies, where model selection or terrain resolution can be adjusted based on expected propagation sensitivity, avoiding unnecessary computational effort (Unger and Kuczmann, 2025b).

From a sustainability perspective, the results demonstrate that terrain-aware hybrid modeling at 3.6 GHz enables a favorable trade-off between accuracy and computational efficiency. By reducing sensitivity to raster resolution while maintaining physically meaningful terrain response, such approaches minimize simulation reruns and energy consumption, contributing to more sustainable spectrum and network planning workflows.

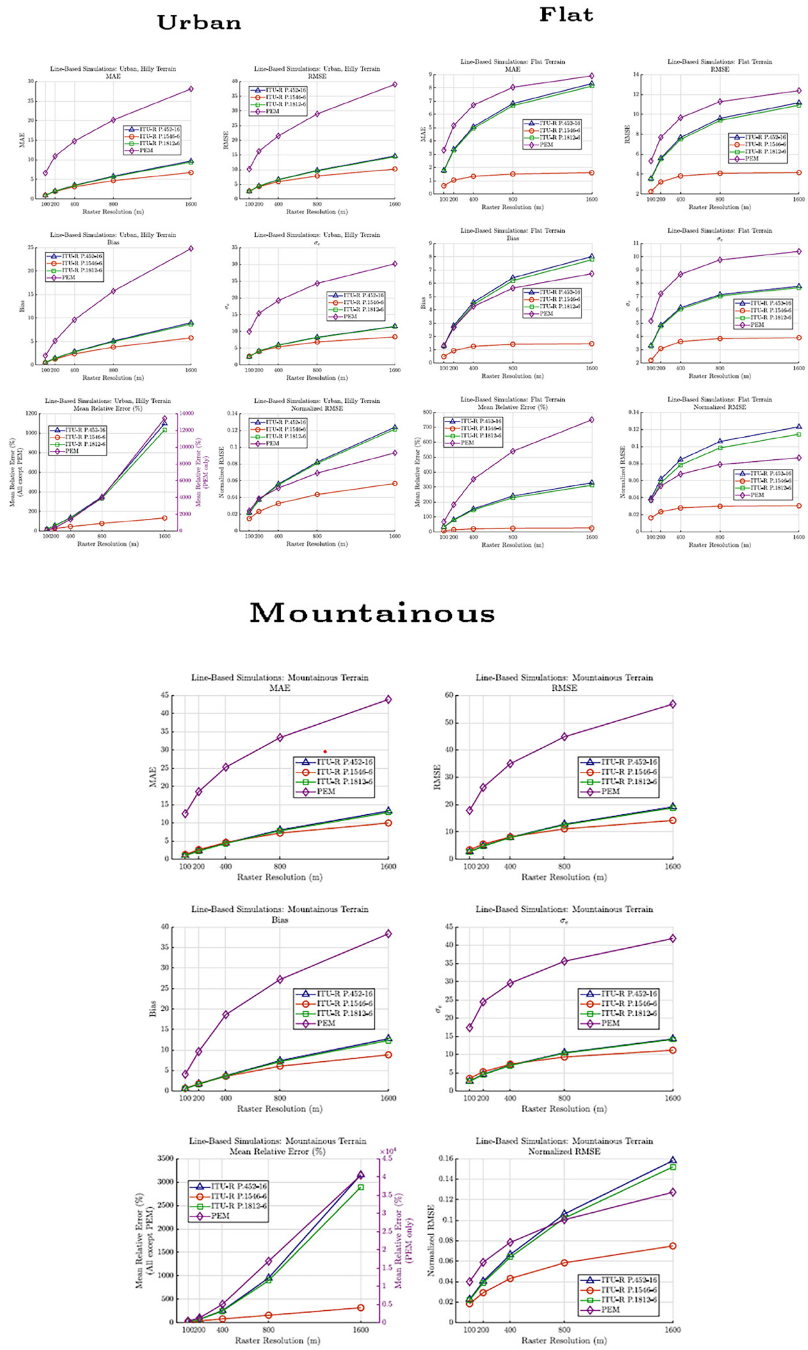


Figure 4: Impact of terrain raster resolution on prediction accuracy at 3.6 GHz for urban, flat, and mountainous environments, shown through multiple error metrics for empirical, hybrid, and deterministic propagation models

6. Conclusions

This paper investigated the performance of widely used propagation models at 3.6 GHz with a particular focus on the relationship between prediction accuracy, terrain sensitivity, and sustainability-related planning aspects. The results demonstrate that these factors are strongly interdependent and have a direct impact on the reliability and efficiency of mobile network design.
Quantitative evaluation showed that empirical models exhibit limited terrain awareness, resulting in high prediction errors and instability as terrain resolution changes. In complex terrain, relative errors exceeding 100 % were observed, together with weak or negative correlation between terrain variability and predicted field strength. In contrast, the deterministic Parabolic Equation Method consistently provided strong terrain sensitivity and served as a reliable reference, but at the cost of high computational complexity.

The hybrid ITU-R P.452-17 model achieved a favorable balance between these extremes. At 3.6 GHz, it reduced RMSE and MAE values by up to several tens of percent compared to empirical approaches, while maintaining a strong positive correlation between terrain variability and field strength variation. The hybrid model exhibited significantly lower sensitivity to terrain raster resolution, indicating improved robustness and reduced need for repeated simulations.
These findings confirm that propagation model selection is not only a technical accuracy issue but also a sustainability-related decision. Terrain-aware hybrid modeling enables reliable predictions with lower computational demand, reducing simulation reruns, planning iterations, and associated energy consumption. Consequently, the results support the use of hybrid propagation models as an effective tool for sustainable and efficient mobile network planning in the 3.6 GHz band.

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