EMF Exposure Constrained Wireless Networks

Shanshan WANG, Télécom Paris
shanshan.wang@telecom-paris.fr

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RSTN - Theoretical foundations of future communication networks

C2M

WHO ARE WE

C2M

- **M**odélisation
- **C**aractérisation
- **M**aîtrise

des **expositions** aux ondes électromagnétiques

https://chairec2m.wp.imt.fr/

ANSES · EXPLORA · exem · SEAWave · GOLIAT

Permanent


Joe Wiart


Shanshan Wang

PostDocs:


Yarui Zhang
2023.01 - now


Samar Chebbi
2025.10 -


Paul Lagouanelle
2025.10 -

PhDs:

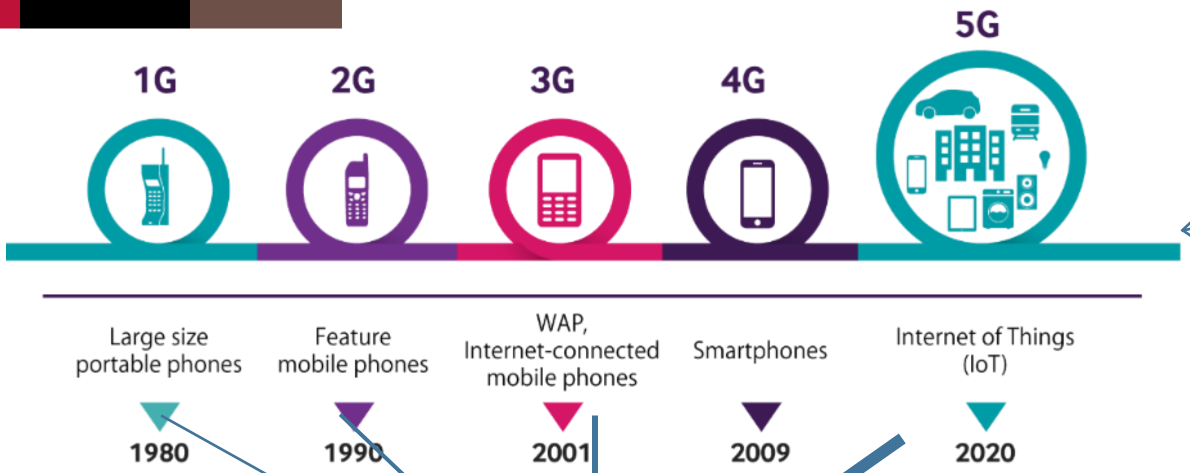

Yukun Liu
2024.11 - 2027.10


Qunfei Sun
2024.10 - 2027.09

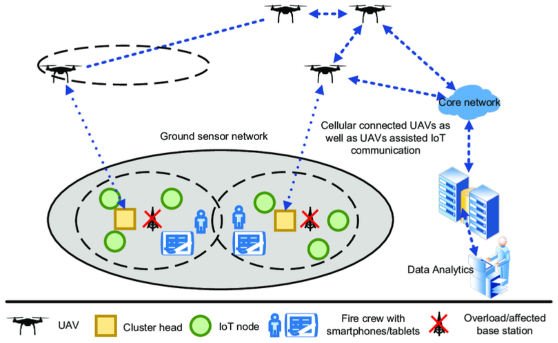

Minh-Huy Nguyen
2025.09 – 2028.08


Shuangning Li
2025.09 – 2028.08

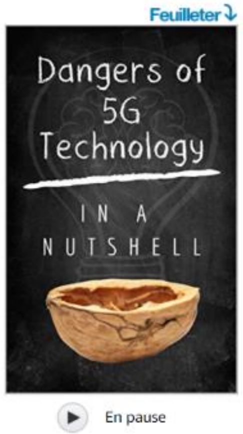
WHAT IS EMF EXPOSURE?

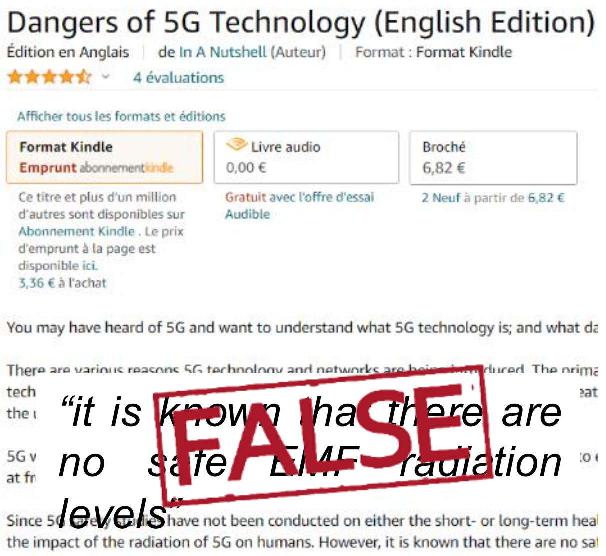


- Wider Spectrum (mmWave)
- High Spectrum Efficiency (Massive MIMO)
- Mass connectivity (IoT, small cells)



Public Concerns on EMF Exposure




Dangers of 5G Technology (English Edition)

Édition en Anglais | de In A Nutshell (Auteur) | Format : Format Kindle

4 évaluations

Afficher tous les formats et éditions

Format Kindle	Livre audio	Broché
Emprunt abonnementkindle	0,00 €	6,82 €
Ce titre et plus d'un million d'autres sont disponibles sur Abonnement Kindle . Le prix d'emprunt à la page est disponible ici. 3,36 € à l'achat	Gratuit avec l'offre d'essai Audible	2 Neuf à partir de 6,82 €

You may have heard of 5G and want to understand what 5G technology is; and what da

There are various reasons 5G technology and networks are being introduced. The prima tech ... the ...

5G v ... at fr ...

Since 5G safety studies have not been conducted on either the short- or long-term heal the impact of the radiation of 5G on humans. However, it is known that there are no saf

"it is known that there are no safe EMF radiation levels"

FALSE

WHAT IS EMF EXPOSURE?

To quantify the EMF exposure level:

Specific absorption rate (SAR) a measure of the rate at which the body absorbs RF energy from an EM field.

$$\text{SAR} = \frac{\text{absorbed power in volume V (watts)}}{\text{mass of the volume V (kg)}}$$

Alternatively,

$$\text{SAR} = \frac{\sigma {E_{RMS}}^2}{\rho}$$

- σ is the conductivity (S/m)
- ρ the mass density (kg/m^3)
- E_{RMS} is the electric field strength (V/m)

Our Objectives:

Take EMF exposure as a constraint in the network design

- **Exposure mapping assisted/aware design**
- **Performance evaluation on EMF exposure from future wireless networks**

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Exposure mapping assisted/aware design

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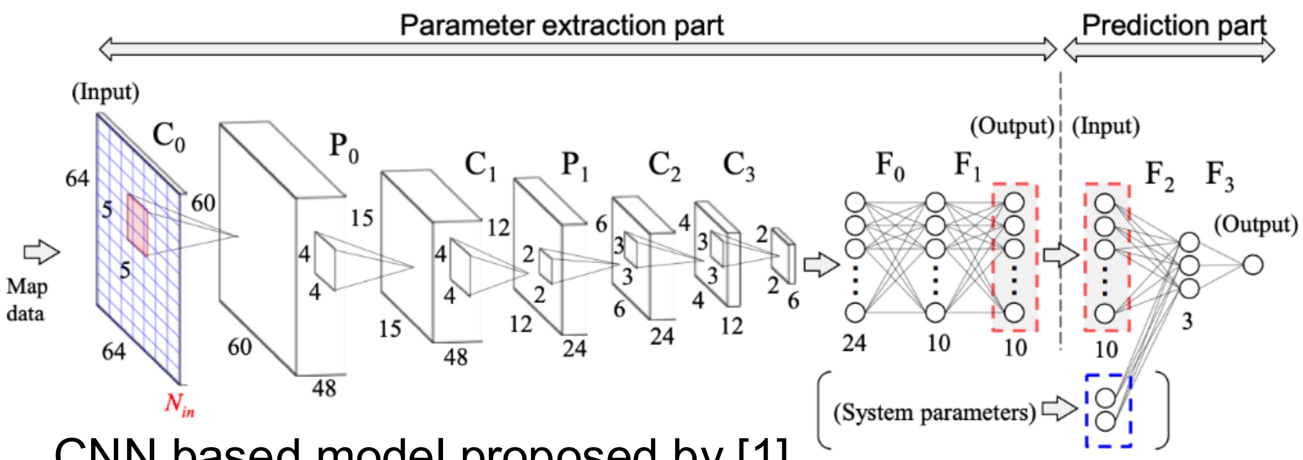
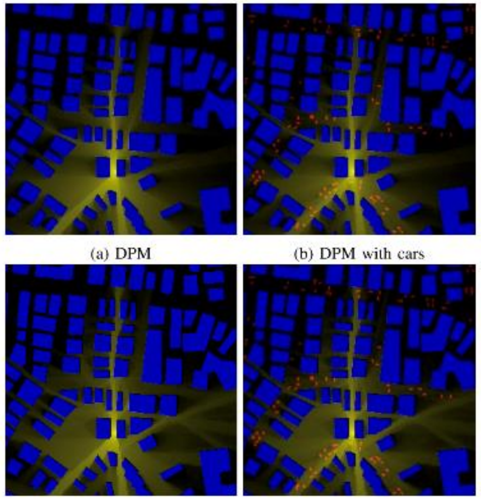
RECENTLY ON RADIO MAPPING



CNN based model proposed by [1]



Radio mapping in outdoor scenario [2]

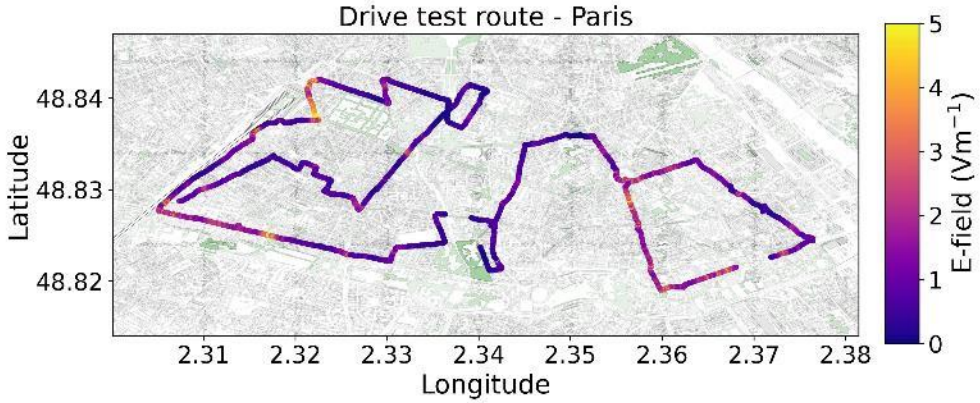
Applications:

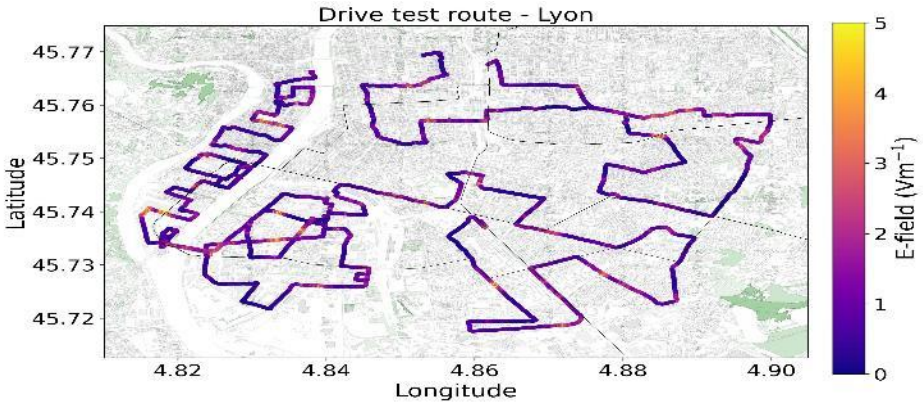
- Radio map-enabled localizations.
- Radio map-assisted integrated sensing and communication.
- Radio map-assisted spectrum sharing.

[1] T. Imai, K. Kitao, and M. Inomata, "Radio propagation prediction model using convolutional neural networks by deep learni ng," in 13th Eur. Conf. Antennas Propag. EuCAP 2019, 2019, pp. 1–5.
[2] R. Levie, c. Yapar, G. Kutyniok, and G. Caire, "Ra- PREPRINT 15 diounet: Fast radio map estimation with convolutional neural networks," IEEE Trans. Wirel. Commun., vol. 20, no. 6, pp. 4001–4015, 2021.

NOVEL DL BASED EXPOSURE MAPPING

Measurement data collection





	Paris	Lyon
Date	2024.01	2023.02
Nb. of points	7516	19062
dis. between 2 pts.	2.76 m	3.36 m
GPS data	CSTB	Geotracker


Tektronix


Tri-axis antenna


Switch+Arduino

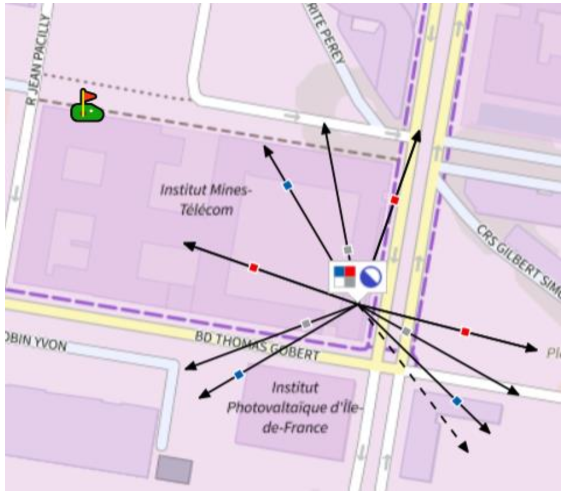

PC

- **E Field**

Measures (MHz): 700, 800, 900, 1800, 2100, 2600, 3500

INPUT DATABASE

1. **Base station antennas (BSAs) channels:** information from cartoradio.fr (ANFR)

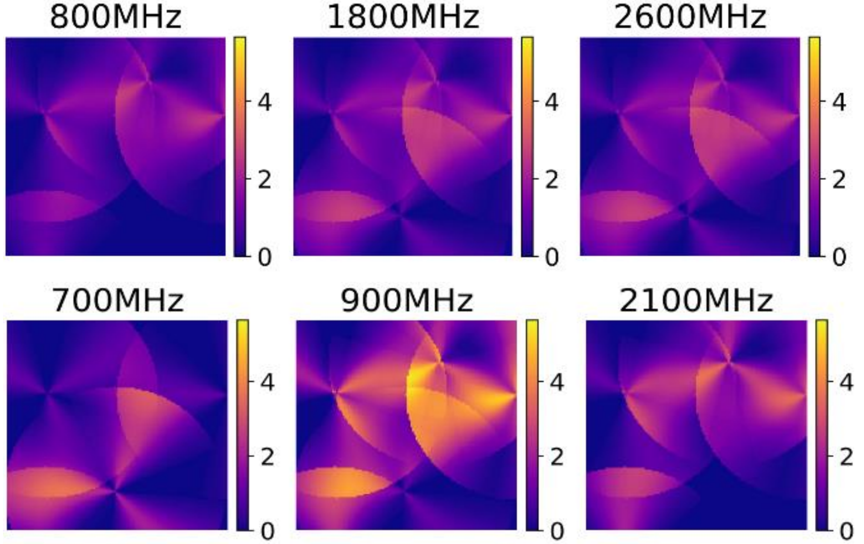


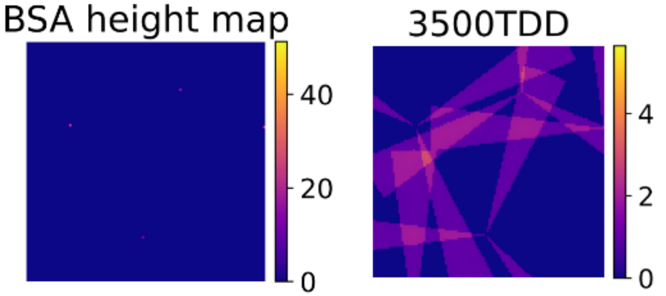
Information available

- Location,
- Height,
- Azimuth,
- Type,
- Operation frequencies

Information not available

- Downtilt,
- Emitted power

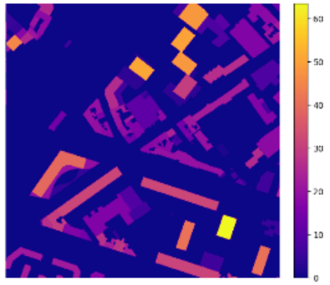




2. **Geospatial channels:** dataset from IGN

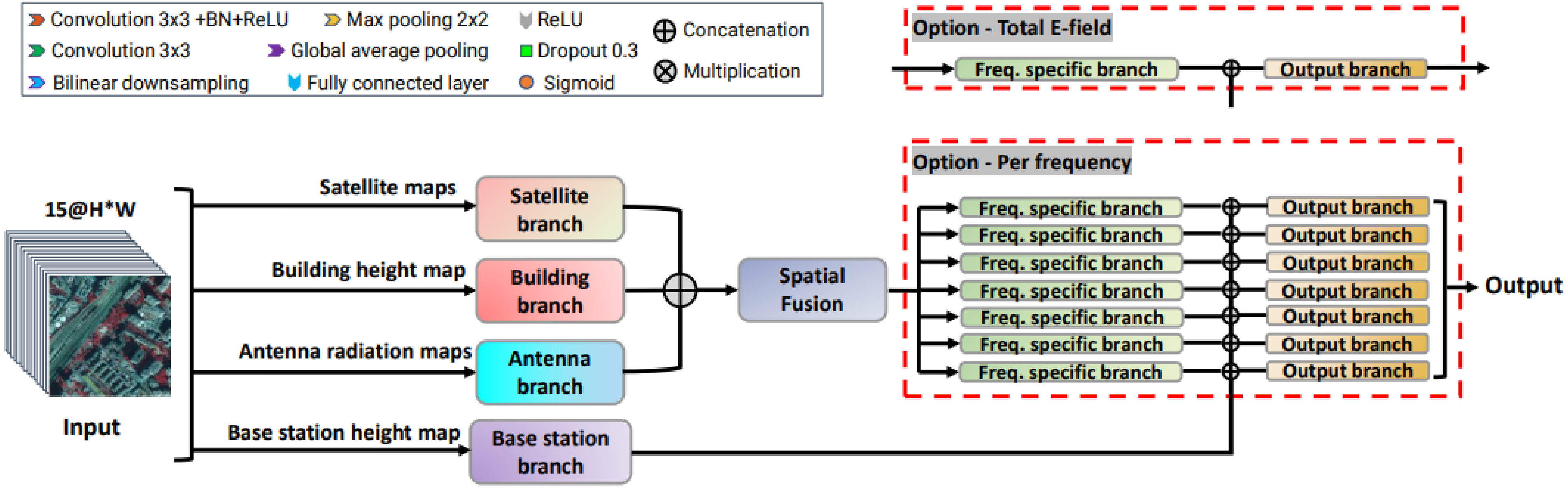
Infrared image

Land cover



Building height

PROPOSED DEEP LEARNING MODEL STRUCTURE



- Specifically designed sub-branches
- Spatial fusion step
- Flexible output layers

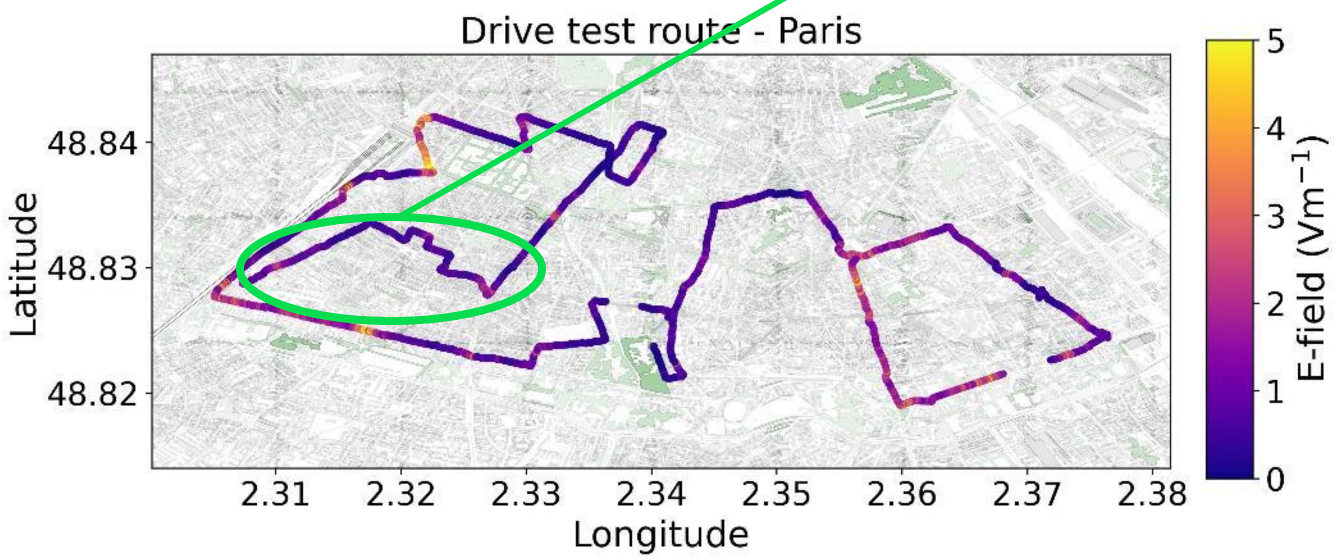
[1] Zhang, Yarui, **Shanshan Wang**, and Joe Wiart. "ExposNet: A deep learning framework for EMF exposure prediction in complex urban environments." Under revision of IEEE Transactions on Antennas and Propagation (2025).

EXPERIMENTAL SETUP

- **Dataset division:**
  In total: 1271 (Lyon) + 418 (Paris) = 1689 samples
  Training : 1539 samples (Lyon + Paris)
  Testing : 150 samples (Paris)
  No dataset shuffling

A segment of route for testing, the remainig part for training

Extrapolation



EXPERIMENTAL SETUP – LOSS FUNCTIONS

- **Basic criterion: Mean Square Error (MSE)**
- **Option - Per frequency:**

$$\mathcal{L}_1 = \mathcal{D} + \lambda \cdot \mathcal{C}$$

$\mathcal{D}$: Data fidelity term; λ: Regularization coefficient; $\mathcal{C}$: Constraint

$$\mathcal{D} = \frac{1}{N_s \times N_f \times 2} \sum_{i=1}^{N_s} \sum_{j=1}^{N_f} \sum_{k=1}^{2} (y_{\text{pred}}[i,j,k] - y_{\text{true}}[i,j,k])^2$$

$$\mathcal{C} = \frac{1}{N_s} \sum_{i=1}^{N_s} (E_{\text{total\_pred}}[i] - E_{\text{total\_true}}[i])^2$$

$i \in [1, N_s]$ is the sample index, j $\in [1, N_f]$ is the frequency band index, $k = 1,2$ corresponds to RMS or STD

- **Option - Total E-field:**

$$\mathcal{L}_2 = \frac{1}{N_s \times 2} \sum_{i=1}^{N_s} \sum_{k=1}^{2} (y_{\text{pred}}[i,k] - y_{\text{true}}[i,k])^2$$

- **Evaluation Metrics:**
  - Root Mean Square Error (**RMSE**)
  - Mean Absolute Percentage Error (**MAPE**)

RESULTS: TESTING ON PARIS'S DATASET

« Option - Per frequency »

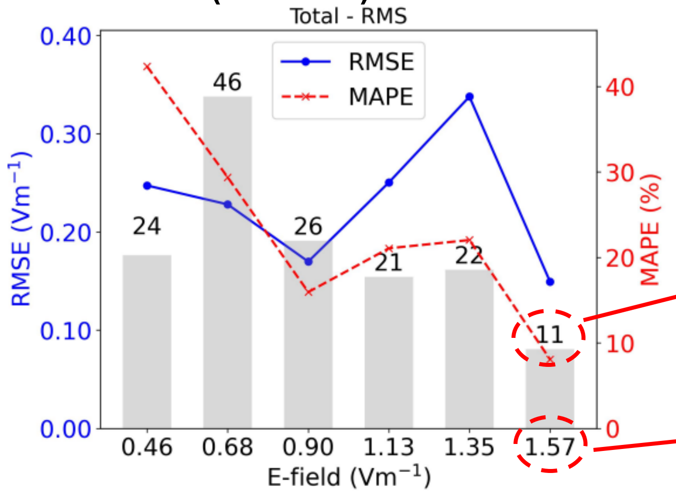
- RMSE ($V\ m^{-1}$) of per-frequency predictions

Freq. (MHz)	700	800	900	1800	2100	2600	3500	Total
RMS	0.129	0.149	0.085	0.125	0.130	0.102	0.058	0.241
STD	0.077	0.099	0.052	0.071	0.083	0.078	0.046	N/A

Highest

Lowest

- RMSE ($V\ m^{-1}$) and MAPE of total E-field values, across different amplitudes



Dataset is divided into 6 equally spaced intervals

Number of samples within each interval

Median of each interval

Overall average **MAPE : 25.32%**
RMSE : 0.24

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RESULTS: TESTING ON PARIS'S DATASET

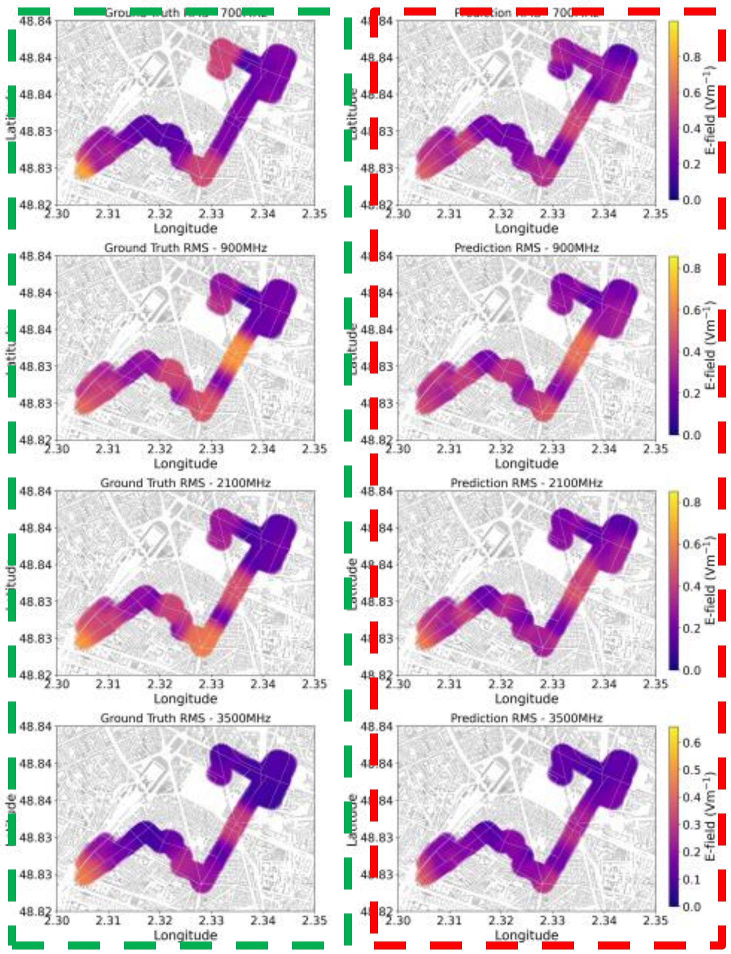
« Option - Per frequency »

700MHz

900MHz

2100MHz

3500MHz

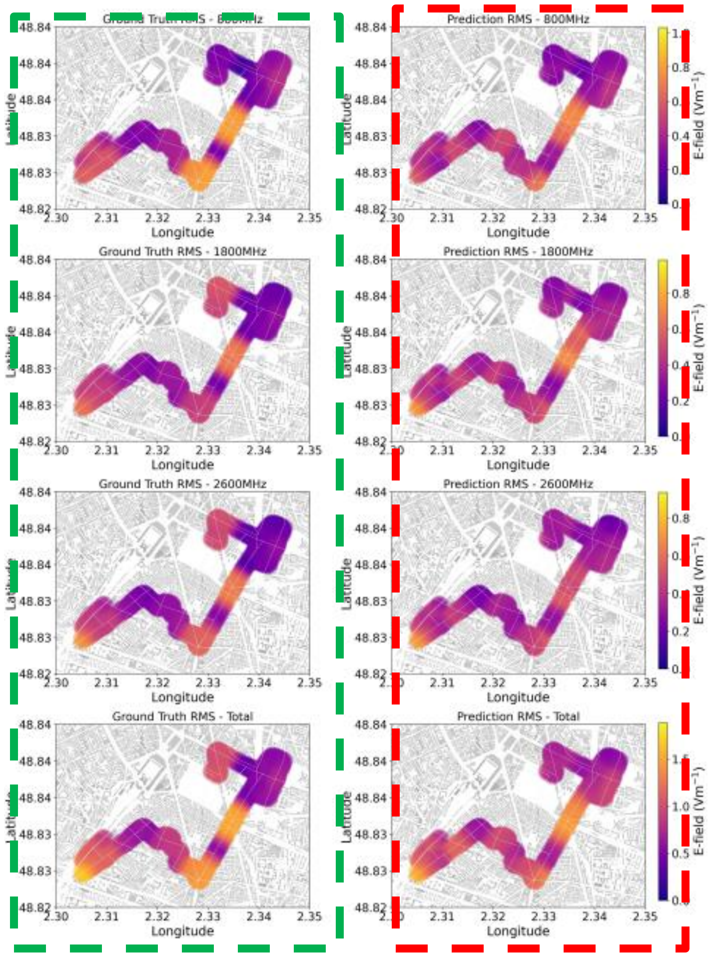


800MHz

1800MHz

2600MHz

Total



Ground truth

Prediction

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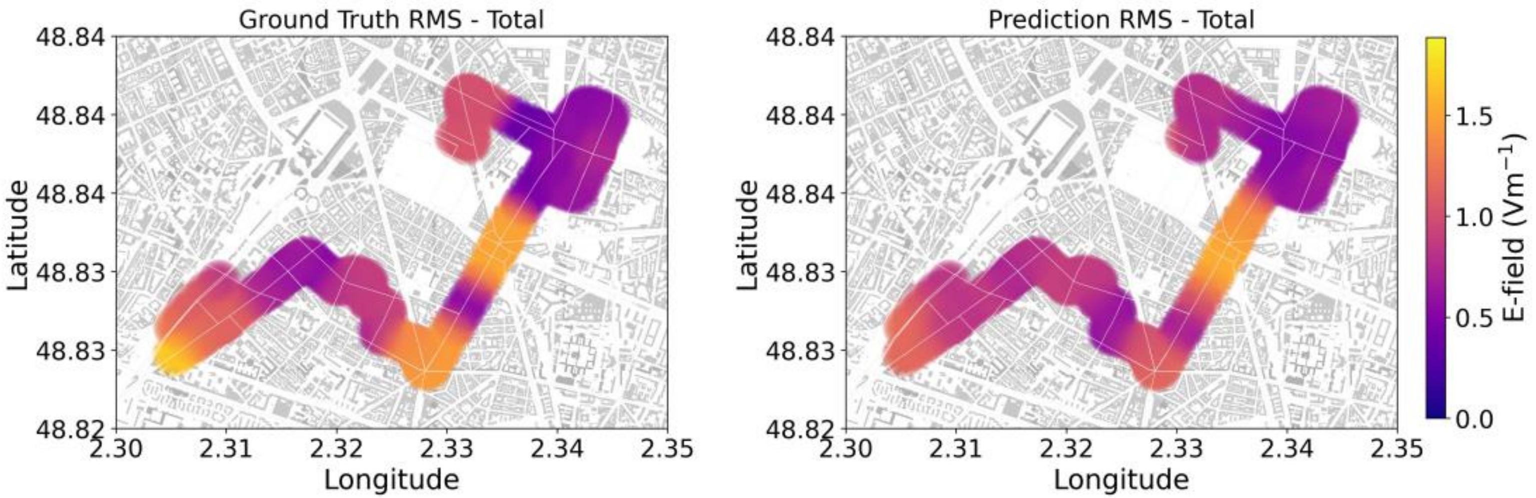
RESULTS: TESTING ON PARIS'S DATASET

« Option – Total E-field»

- RMSE ($V\ m^{-1}$) and MAPE of predictions

Target\Metric	RMSE	MAPE (%)
RMS	0.231	20.353
STD	0.153	27.127

- Visualization of results



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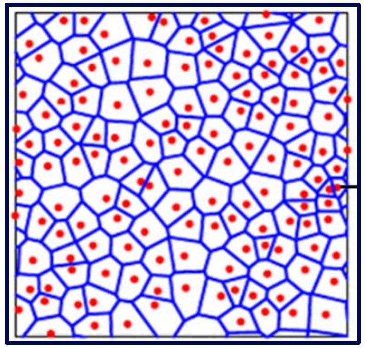
Performance evaluation on EMF exposure from future wireless networks

STOCHASTIC MODELING OF EXPOSURE

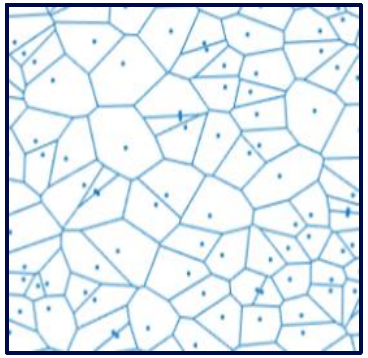
- Stochastic geometry allows the analysis of metrics of random network models

➢ **Could be used in modeling the exposure**

Exposure (E field) ~ $P_{rx} = \sum P_{tx} |h_i|^2 r_i^{-\alpha}$



Actual 4G network

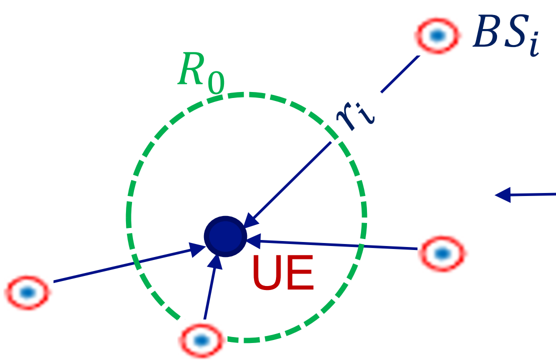


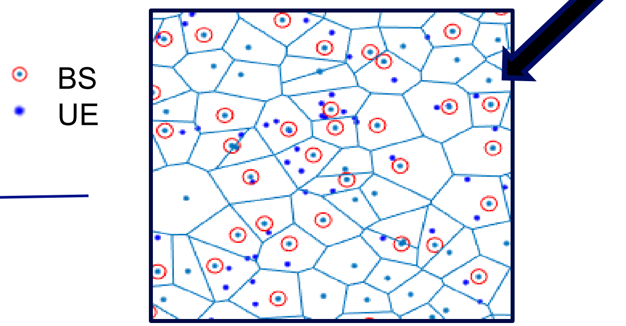
Poisson point process grid

The CDF of the power can be determined using Gil-Peleaz inversion

$$F_{P_{rx}}(x) = \frac{1}{2} - \frac{1}{\pi} \int_0^\infty \frac{1}{t} \Im\left[e^{-jtx} \mathrm{MGF}_{P_{rx}}(-jt)\right] dt$$

$\mathrm{MGF}(x)$: Moment generating function





BSs and UEs distributed as PPP

CHARACTERIZATION OF EMF EXPOSURE

Challenges: Realistic modeling of 5G Massive MIMO networks[1]

- Massive MIMO
- Digital Beamforming
- Single User
- NYUSIM Simulator

Array Gain: $f_G(g) \approx a \exp(-ag)$

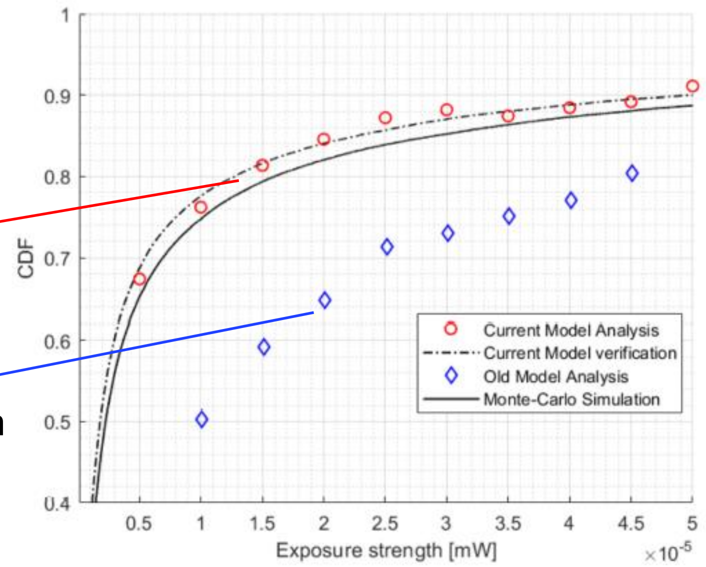
Channel Gain: $f_H(h) \approx \frac{1}{\Gamma(b) c^b} h^{b-1} \exp(-h/c)$

The distribution of total received power (exposure) [1]

$$F_{P_{rx}}(x) = \Pr\{P_{rx} \le x\}, P_{rx} = \sum_{BS_i \in \Psi_{BS}} P_{tx} H_i G_i L_i$$

Simple model

- Isotropic antenna gain
- Rayleigh fading



[1] M. Al Hajj, **Shanshan Wang**, L. T. Tu, S. Azzi, J. Wiart., Applied Sciences, 10(23), 8753.

STOCHASTIC MODELING OF EXPOSURE

System model

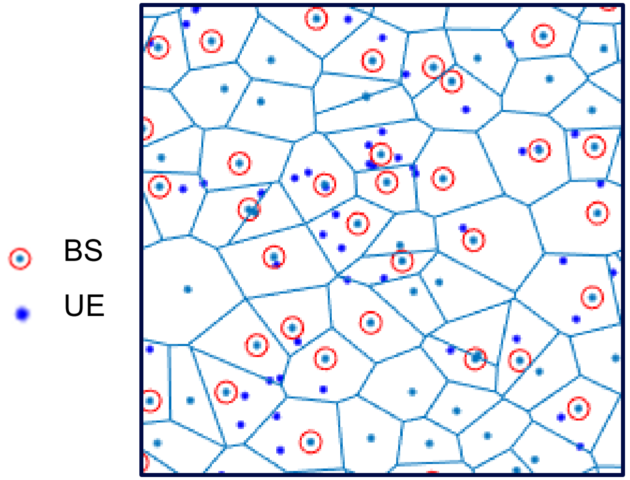
- Downlink multi-cell, multi-user massive MIMO network
- BSs and UEs modeled as PPPs Φ_{BS} and BPP Φ_{UE} on $\mathbb{R}^2$
- Large scale fading (BS_l and MT_k): $\beta_{lk}(R_{lk}) = \max(d, R_{lk})^{-\alpha}$
- Small scale fading: $h_{lk} \sim \mathcal{CN}(0, I_M)$, i.i.d. Rayleigh fading
- Precoding: Maximum ratio transmission (MRT): $a_{lk}^S = \frac{1}{\sqrt{M}} h_{lk}^*$
- Average power received

$$E = S + I_M + I_I$$

Average useful signal (S)

Average multi-user interference (I_M)

Average inter-cell interference (I_I)



Φ_{BS} and Φ_{UE}

STOCHASTIC MODELING OF EXPOSURE

- Max-Min Fairness Power Control: to ensure equal SIR for all served UEs.
- Power control coefficient at the nearest MT to its BS η_{l0} as

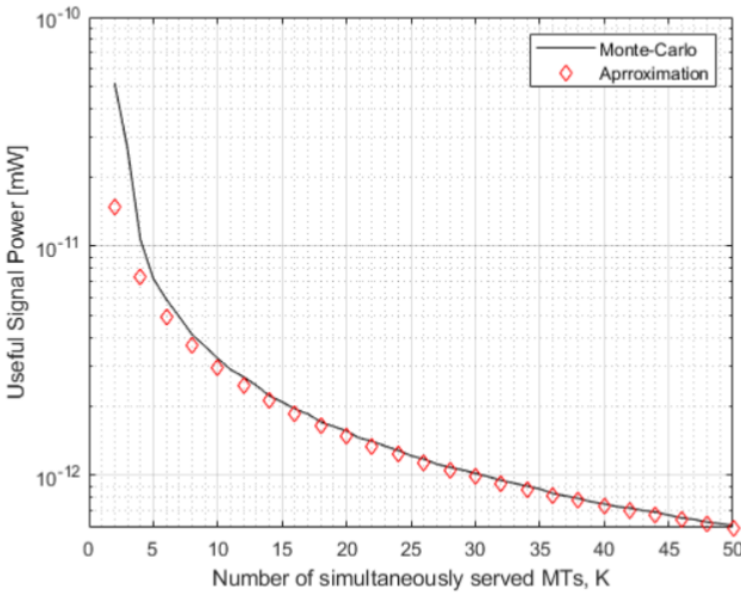
$$\eta_{l0} = \frac{1+\rho_{dl}\beta_{l0}}{\beta_{l0}\sum_{k\in\Phi_{MT}}\frac{1+\rho_{dl}\beta_{lk}}{\beta_{lk}}}$$

Not tractable

➢ **Proposition 1. We approximate it using the law of large numbers**

$$\eta_{lk} \approx \frac{1+\rho_{dl}\beta_{lk}}{\beta_{lk}\left(K\rho_{dl}+K_L\overline{\Upsilon}(\alpha_L)+K_N\overline{\Upsilon}(\alpha\_N)\right)}$$

where $\overline{\Upsilon}(\alpha_S)$ is the expectation of $\left(\beta_{lk'}^{S}\right)^{-1}$



Average signal power to verify validity of the approximation

$S = \rho_{dl}\mathbb{E}[\eta_{l0}\beta_{l0}^{S}]$

STOCHASTIC MODELING OF EXPOSURE

Derivation of The Average Power Received

$$\mathcal{S} = M\rho_{dl}\left(1 + \rho_{dl}p_L\mathcal{Q}_{l0}^L + \rho_{dl}p_N\mathcal{Q}_{l0}^N\right)\mathcal{L},$$

$$\mathcal{I}_I = 2\pi\lambda_{BS}\rho_{dl}\left(\frac{d^{2-\alpha_N}}{2} + \frac{d^{2-\alpha_N}}{\alpha_N - 2}\right) - \left(p_L\mathcal{Q}_{l0}^L + p_N\mathcal{Q}_{l0}^N\right)$$

$$\mathcal{I}_M = \rho_{dl}\left(p_L\mathcal{Q}_{l0}^L + p_N\mathcal{Q}_{l0}^N\right)\frac{(1-p_L)^K}{K(\rho_{dl} + \bar{\Upsilon}(\alpha_N))} \times {}_2F_1\left(-K, \frac{K(\rho_{dl} + \bar{\Upsilon}(\alpha_N))}{\bar{\Upsilon}(\alpha_L) - \bar{\Upsilon}(\alpha_N)}; \frac{K\rho_{dl} + \bar{\Upsilon}(\alpha_L) + (K-1)\bar{\Upsilon}(\alpha_N)}{\bar{\Upsilon}(\alpha_L) - \bar{\Upsilon}(\alpha_N)}; \frac{p_L}{p_L - 1}\right)$$

$$\mathcal{Q}_{l0}^S = \frac{d^{-\alpha_S-1}}{4K^2-1}\left(\left(1 - \frac{d^2}{R^2}\right)^K \left(d^2(2K-1) + R^2\right) - R^2\,{}_2F_1\left(-\frac{1}{2}, 1-K; \frac{1}{2}; \frac{d^2}{R^2}\right)\right) + \frac{\Gamma\left(\frac{-\alpha_S+3}{2}\right)}{2R^2}\left(\frac{\Gamma(K)R^{-\alpha_S+3}}{\Gamma\left(K + \frac{-\alpha_S+3}{2}\right)} - d^{-\alpha_S+3}\,{}_2\tilde{F}_1\left(1-K, \frac{-\alpha_S+3}{2}; \frac{-\alpha_S+5}{2}; \frac{d^2}{R^2}\right)\right)$$

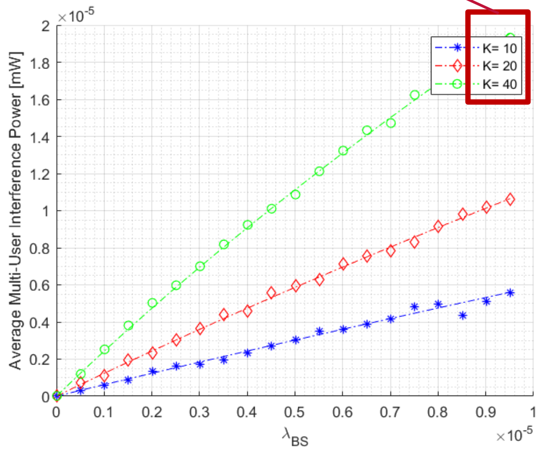
STOCHASTIC MODELING OF EXPOSURE

Numerical Results – Average Power

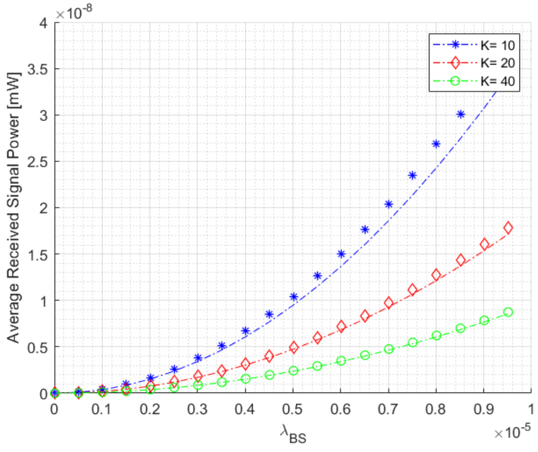
Number of Served UEs

Lines: Analytical Framework

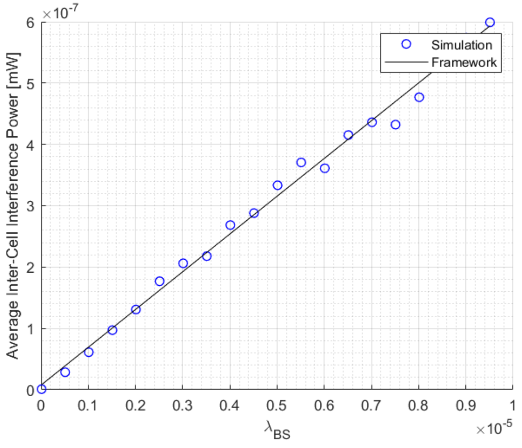
Markers: Monte-Carlo



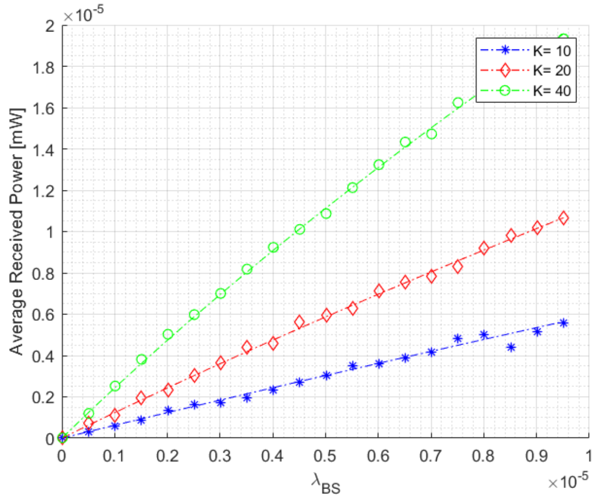
(a) Multi-user interference



(b) Useful signal



(c) Inter-cell interference



(d) Total power received

[1] Al Hajj, Maarouf, **Shanshan Wang**, and Joe Wiart. EuCAP, pp. 1-5. IEEE, 2022.

STOCHASTIC MODELING OF EXPOSURE

Maximize coverage vs. minimize EMF exposure?

Joint distribution of Coverage and EMF Exposure: $G(T,T') @ \mathbb{E}\left[\mathbb{P}\left[\frac{S_0}{I_0+\sigma^2} > T, S_0 + I_0 < T'\right]\right]$

System Model:

$l(r_i) = \kappa^{-1}\left(r_i^2 + z^2\right)^{-\alpha/2}$

$|h_i|^2 \sim \text{Rayleigh}$

\+

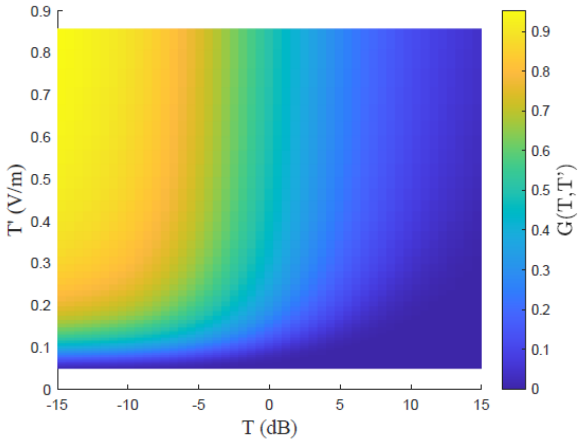
Realistic BS database:

- Paris' 5G NR 2100 band
- Brussels' LTE 1800 band

→ $\beta - \text{GPP}$

→ I-PPP with a radial intensity measure

$$G(T,T') @ \begin{cases} \beta \sum_{i\in\mathbb{N}_0} \int_{\frac{c r_e^2}{\beta}}^{\frac{c\tau^2}{\beta}} \frac{s^{i-1}e^{-s}}{(i-1)!}\left(\frac{1}{2}F_X\left(\frac{T'}{P_t\, l(\beta s/c)}\right)\Upsilon_i^\beta\left(s,\frac{c\tau^2}{\beta}\right) - \frac{1}{\pi}\int_0^\infty \text{Im}\left[\phi_I(q|\beta s/c)\zeta(T,T',l(\beta s/c))\right] q^{-1}dq\right) ds \\ \int_{\theta_0}\int_{r_0}\left[\frac{1}{2}F_X\left(\frac{T'}{P_t\, l_0}\right) - \int_0^\infty \frac{1}{\pi q}\text{Im}\left[\phi_I(q|r_0,\theta_0)\,\zeta(T,T',l_0)\right]\right] f_{R_0,\Theta_0}(r_0,\theta_0)dr_0\, d\theta_0 \end{cases}$$



Paris 5G NR 2100 MHz β-GPP

[1] Gontier, Q., Wiame, C., **Wang, S.**, Di Renzo, M., Wiart, J., Horlin, F., Tsigros, C., Oestges, C., and De Doncker, F., "Joint metrics for EMF exposure and coverage in real-world homogeneous and inhomogeneous cellular networks", IEEE Transactions onWireless Communications 2024

SUMMARY AND PERSPECTIVES

Perspectives:

- **Exposure mapping** or spectrum sensing, energy harvesting …
- **Uncertainty quantification** in the AI models *– PhD starts from 11/2024*
  - Aleatoric: Dynamic radio environment, traffic load from BS; Performance of measurement device
  - Epistemic: Uncertainty from the in-sample and out-of-sample prediction.
- **Physics assisted/informed** neural networks *– PhD starts from 09/2025*
- **EMF-aware** design of networks are integrated with more emerging techniques, such as
  - Integrated sensing and communications (ISAC) – *PhD starts from 09/2025*