EMF Exposure in the Evolution from Current to Future Wireless Networks

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04.02.2025

WHO ARE WE

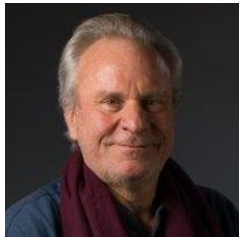
C2M

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

des **expositions** aux ondes électromagnétiques

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

Permanent (LTCI part):



Joe Wiart

Shanshan Wang

Christophe Roblin

PostDocs:

Yarui Zhang

2 to be recruited

PhDs:

Yukun Liu

to be recruited

WHO ARE WE

5 Axes in Chair C2M:

- **Numerical** and **experimental** dosimetry
- **Statistical modeling** of exposure, stochastic dosimetry
- **Influence** of network technologies and architectures on exposure
- **Standardization** of exposure assessment methods
- Parameters governing the social **perception of risk**

OUTLINE

- Introduction to EMF Exposure to Human Health
- Assessments of RF-EMF Exposure
- AI methods-based prediction
- Stochastic Modeling of Exposure
- Summary and Perspectives

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- Assessments of RF-EMF Exposure
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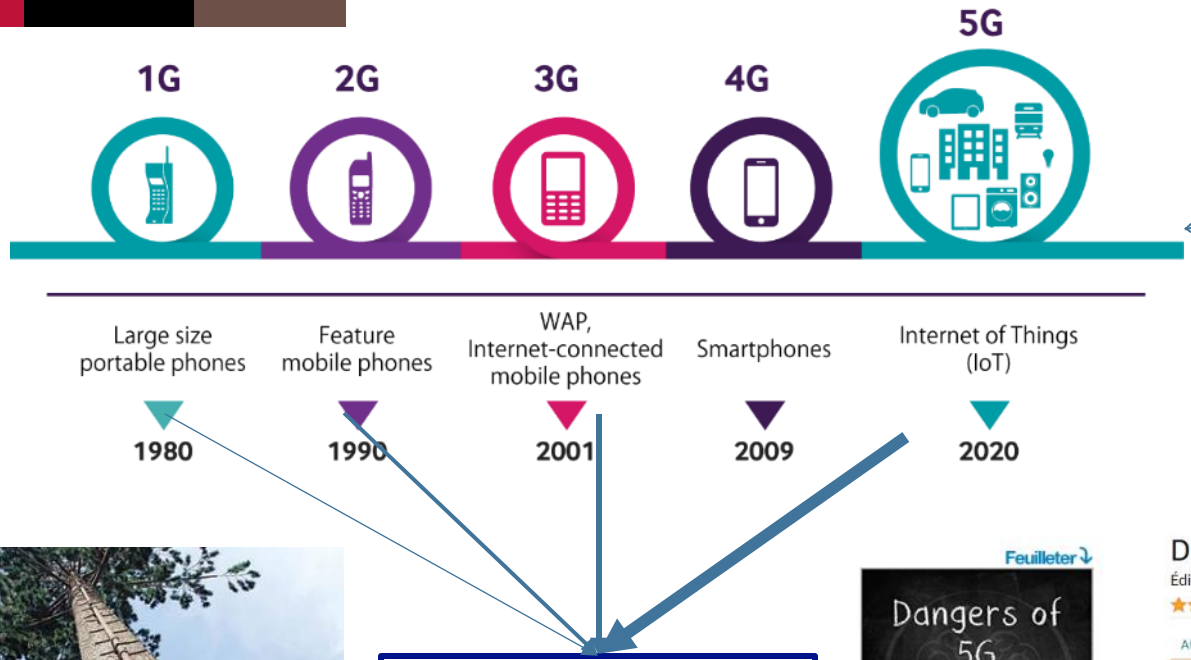
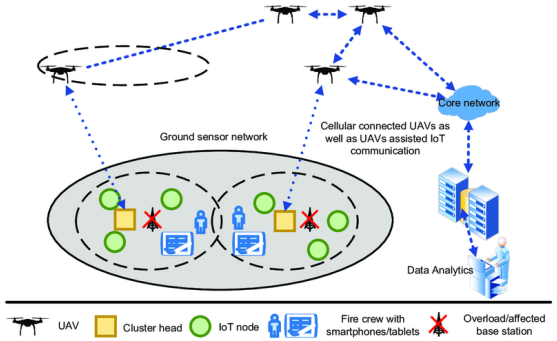
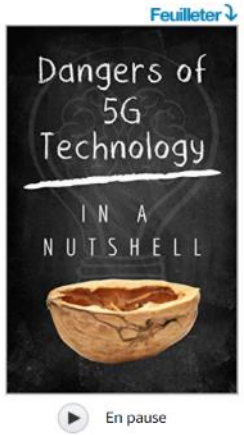
WHAT IS EMF EXPOSURE?



- 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

at fr

Since 5G [illegible] 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 sa

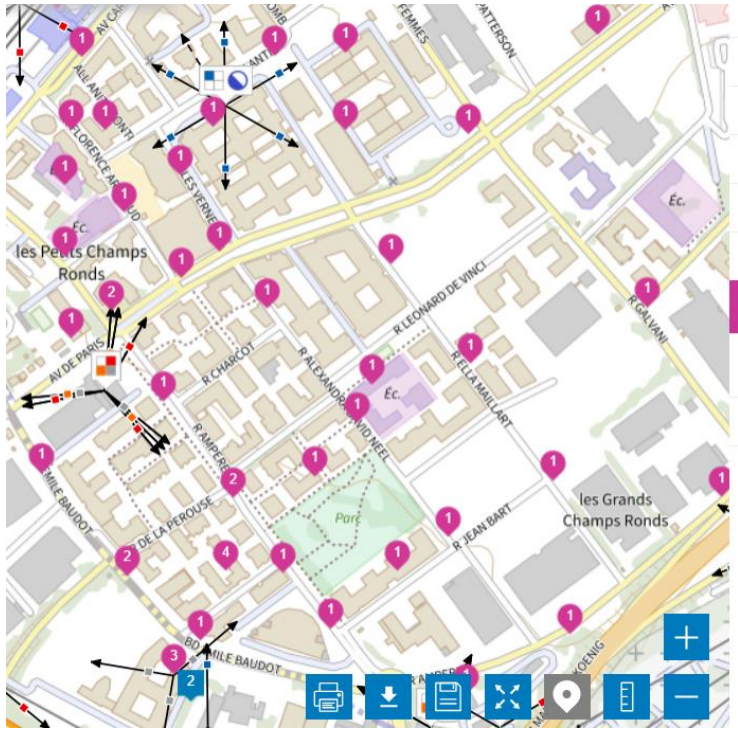
"it is known that there are no safe EMF radiation levels"

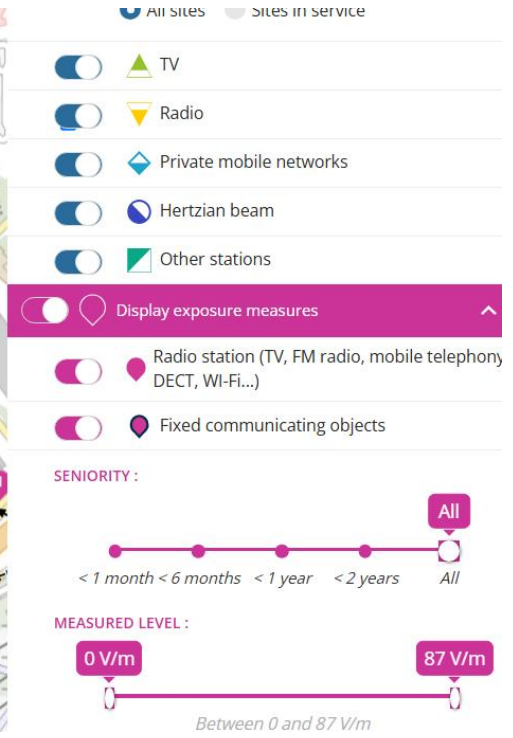
FALSE

WHAT IS EMF EXPOSURE?

Authorities:

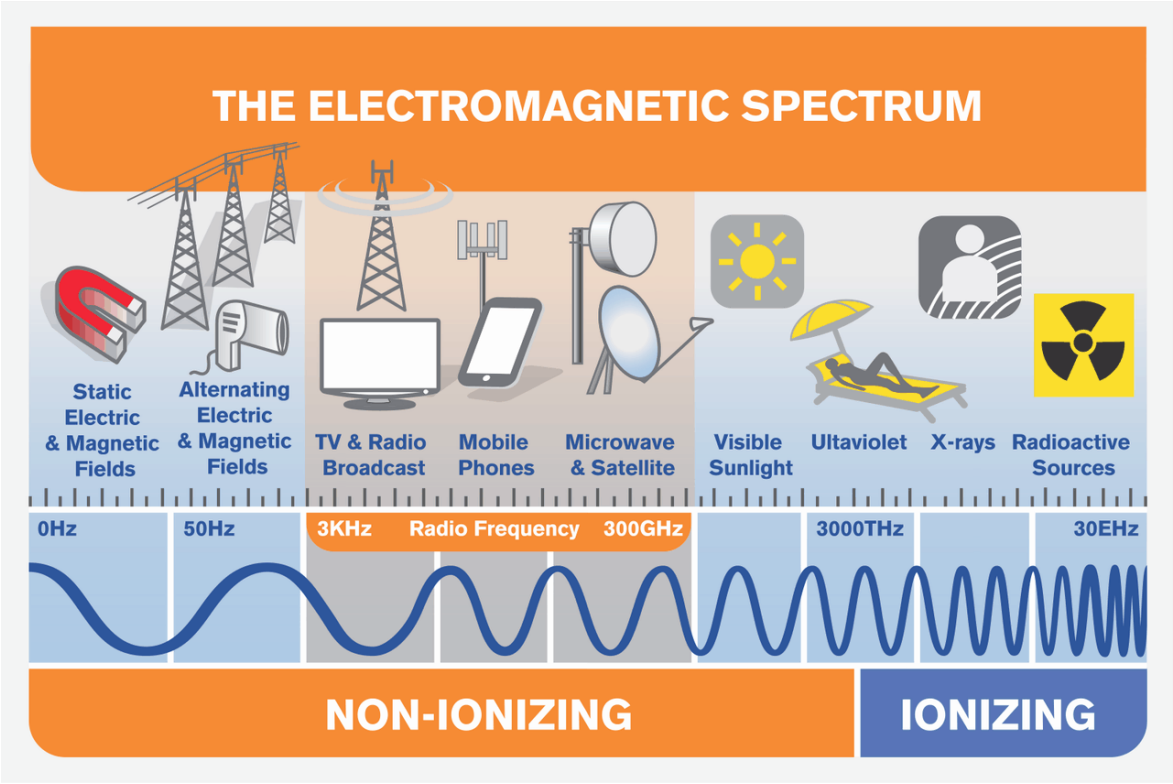
- ICNIRP safety guidelines on EMF exposure: 61V/m for radio frequency (up to 2GHz);
- IEC/CENELEC has designed standards for measurement and calculation of EMF exposure.
- The National Frequency Agency (ANFR) provide public accessed database with information of BSs and EMF measurements;





Does EMF Exposure lead to adverse health effects?

WHAT IS EMF EXPOSURE?



Specific absorption rate (SAR) a measure of the rate at which the body absorbs RF energy from an EM field. It is defined as ratio of **electromagnetic power absorbed (watts) by tissues** to **the mass (kg) of these tissues**. It is defined as

$$\mathrm{SAR} = \frac{\text{absorbed power in volume V}}{\text{mass of the volume V}}$$

Relationship between SAR and electric field:

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

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

WHAT IS EMF EXPOSURE?

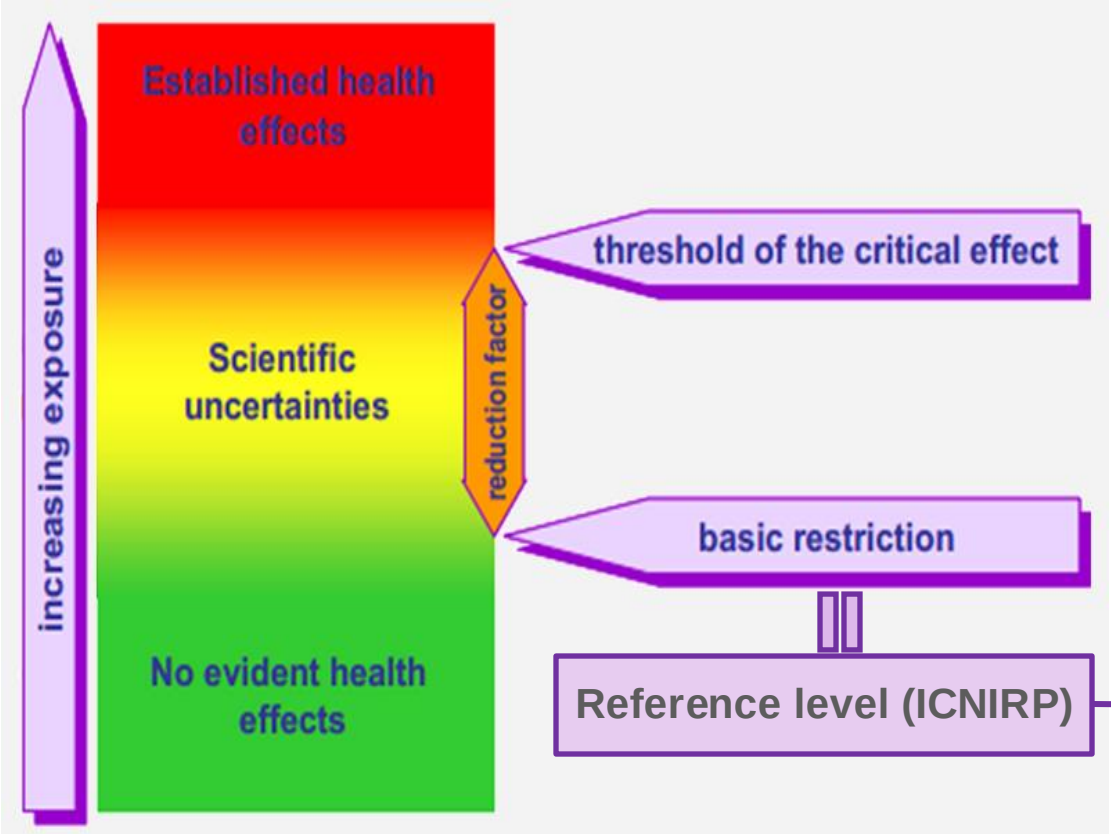
Scientific Basis [1]:

Only adverse health effects

- **Heating** (from ~100kHz)
- Nerve stimulation (up to ~10MHz)

No evidence for

- Cancer
- Electrohypersensitivity
- Infertility
- Other health effects



For the whole body exposure higher than 4 W/kg for longer than **30 min**, the rise in human body temperature can be higher than 1°C

↓

10 times below, in SAR (W/Kg) and APD (W/m^2)

E Field (V/m) corresponding basic restrictions in W/Kg

↓

Reference level (Each country) No greater than Ref level

1. https://www.icnirp.org/en/activities/news/news-article/rf-guidelines-2020-published.html

WHAT IS EMF EXPOSURE?

Table 1 Reference levels or exposure limits for the general public for electromagnetic fields in inhabited areas in member states of the European Union and selected industrial nations outside the European Union (situation July 2017)

	50 Hz		900 MHz			1800 MHz			2100 MHz		
Country:	electric field strength (V/m)	magnetic flux density (μT)	electric field strength (V/m)	magnetic flux density (μT)	equivalent plain wave power density (W/m^2)	electric field strength (V/m)	magnetic flux density (μT)	equivalent plain wave power density (W/m^2)	electric field strength (V/m)	magnetic flux density (μT)	equivalent plain wave power density (W/m^2)
1999/519/EC	**5000**	**100**	**41**	**0.14**	**4.5**	**58**	**0.20**	**9**	**61**	**0.20**	**10**
Austria	[5000]	[100] [1]	[41]	[0.14]	[4.5]	[58]	[0.20]	[9]	[61]	[0.20]	[10]
Belgium	—	10 [2]	21 [3]	—	—	29 [3]	—	—	31 [3]	—	—
Bulgaria	— [4]	— [4]	—	—	0.1	—	—	0.1	—	—	0.1
Croatia	2000 [5]	40 [5]	17 [5]	0.055 [5]	0.72 [5]	23 [5]	0.078 [5]	1.4 [5]	25 [5]	0.084 [5]	1.7 [5]
Cyprus	[5000]	[100]	41	0.14	4.5	58	0.20	9	61	0.20	10
Czech Republic	2000	200	41	0.14	4.5	58	0.20	9	61	0.20	10
Denmark	—	— [6]	—	—	—	—	—	—	—	—	—
Estonia	5000	100	41	0.14	4.5	58	0.20	9	61	0.20	10
Finland	[5000]	[100] [7]	41	0.14	4.5	58	0.20	9	61	0.20	10
France	5000 [8]	100 [8]	41	0.14	4.5	58	0.20	9	61	0.20	10
Germany	5000 [9]	100 [9]	41	0.14	4.5	58	0.20	9	61	0.20	10
Greece	5000	100	32 [10]	0.11 [10]	2.7 [10]	45 [10]	0.15 [10]	5.4 [10]	47 [10]	0.16 [10]	6 [10]
Hungary	5000	100	41	0.14	4.5	58	0.20	9	61	0.20	10
Ireland	5000 [11]	100 [11]	41	0.14	4.5	58	0.20	9	61	0.20	10
Italy	—	3 [12]	6 [13]	0.02 [13]	0.1 [13]	6 [13]	0.02 [13]	0.1 [13]	6 [13]	0.02 [13]	0.1 [13]
Latvia	—	—	—	—	—	—	—	—	—	—	—
Lithuania	500 [14]	20 [14]	—	—	0.45	—	—	0.9	—	—	1

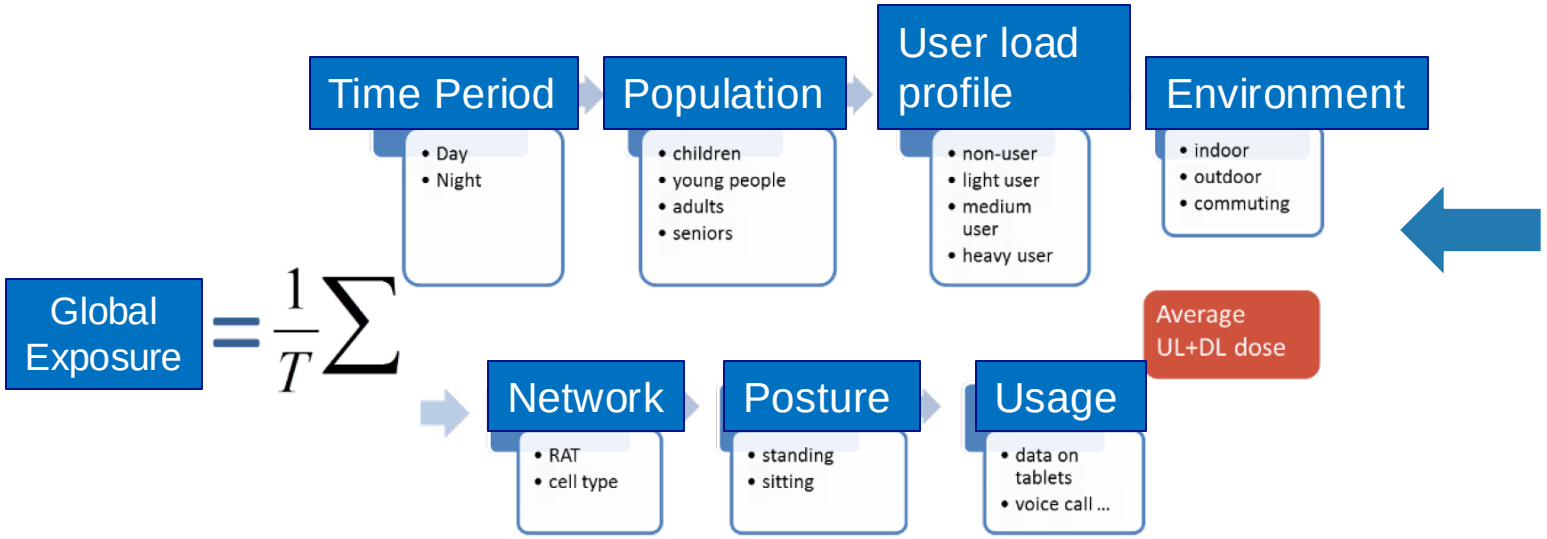
Most countries follow ICNIRP reference level

Is it enough?

Reference level is defined based on short period experiments (6min/30min).

Cumulative long term effect of EMF exposure has not been proven, but is still under investigation (with epidemiologists)

WHAT IS EMF EXPOSURE?



Our Objectives:

- **Monitor time variation on EMF RF exposure**
- **Monitor spatial variation on EMF RF exposure**
- **Adapt to dynamic environments on EMF RF exposure (Outdoor, Indoor)**
- **Statistical distribution of EMF exposure**

- **In situ measurement**
  - Sensor networks
  - Spot measurement
  - Drive test
- **AI based Prediction**
- **Mathematical modeling**

+

Realistic Exposure Level

+

Collaboration with Epidemiologist

OUTLINE

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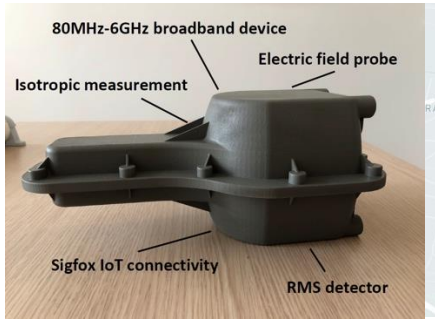
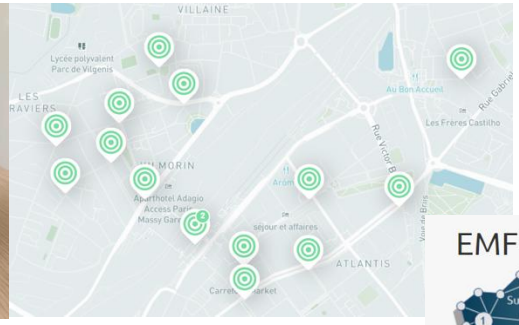
MEASUREMENT CAMPAIGNS ON EMF EXPOSURE

Vast Measurement campaigns:

1. Sensor networks: France, Greece, Serbia, Spain…

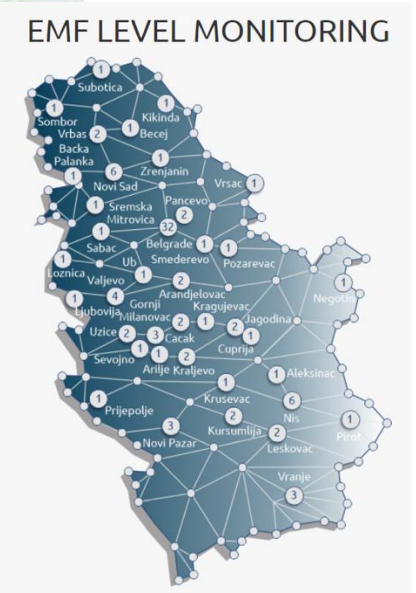
The **time-variation** of the total exposure





France

Greece



Serbia

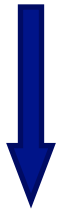
Funded by SEAWave project

Partners:

MEASUREMENT CAMPAIGNS ON EMF EXPOSURE

Vast Measurement campaigns:

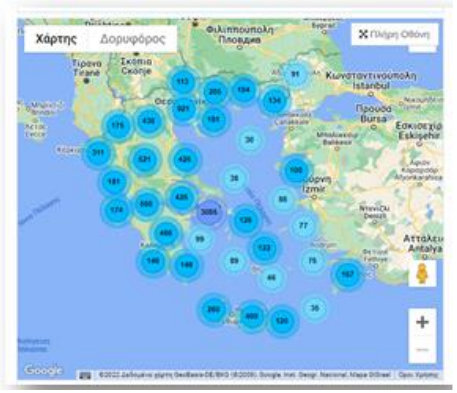
2. Spot measurements: France, Greece, japan, Germany



The **spatial-variation** of EMF exposure

France: Measurements in city halls

Greece[2]



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Partners:

1 https://paratiritirioemf.eeae.gr/el/

MEASUREMENT CAMPAIGNS ON EMF EXPOSURE

Vast Measurement campaigns:

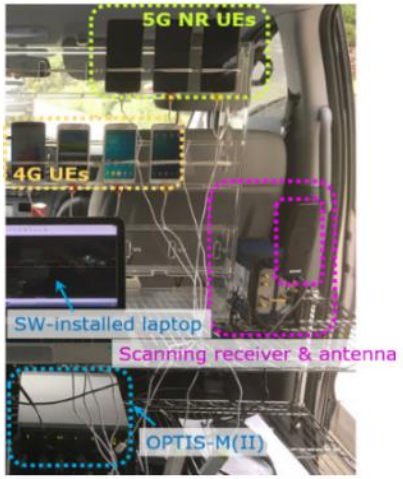
3. Drive test: France, Japan, Korea

The **spatial-variation** of EMF exposure

The **time-variation (daily)** of EMF exposure

France

Greece

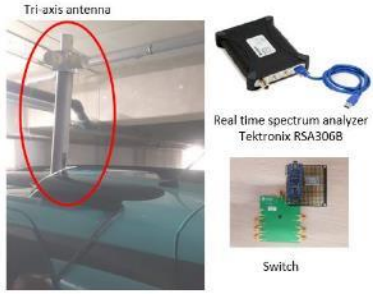


Korea

Partners:

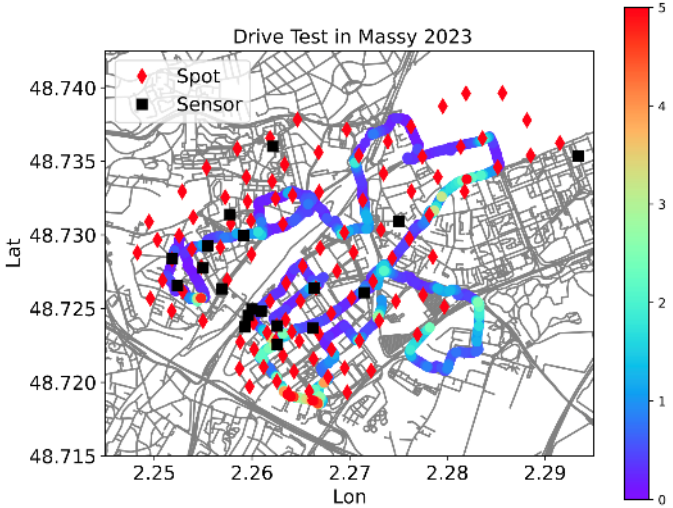
STATISTICAL ANALYSIS ON EMF EXPOSURE

Outdoor + Downlink



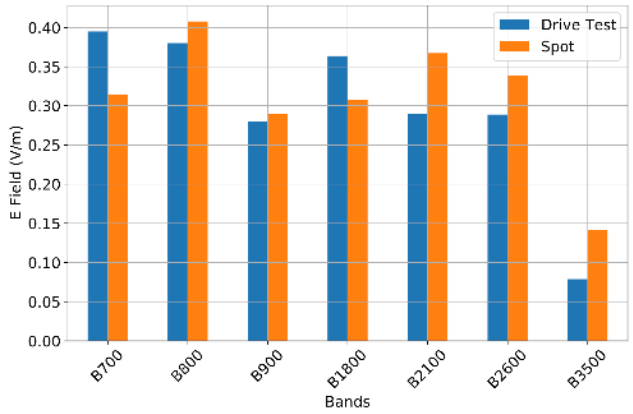
Drive Test: Tektronix RSA 306B

Spot: SRM 3006



- **3672** points in Drive test
- **100** spot measurements
- **15** sensors

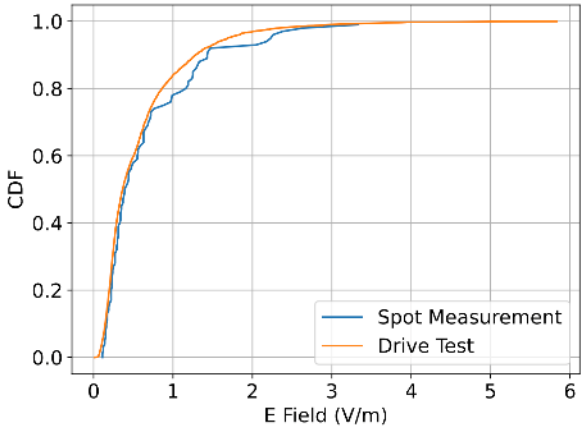
→ Temporal variation



Statistical distribution:

← By frequency band

Total E field →



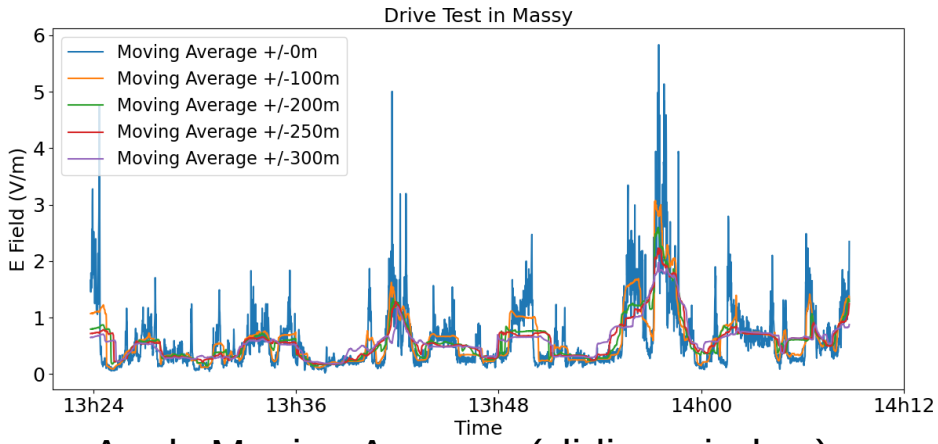
*[1] **Wang, Shanshan**, et al. "RF Electromagnetic Fields Exposure Monitoring using Drive Test and Sensors in a French City." 2023 URSI GASS. IEEE, 2023.*

Supported by EU's Horizon Europe Framework Program under Grant N° 101057622 (SEAWave** Project).*

STATISTICAL ANALYSIS ON EMF EXPOSURE

Outdoor + Downlink

Drive Test vs. Spot [1]*

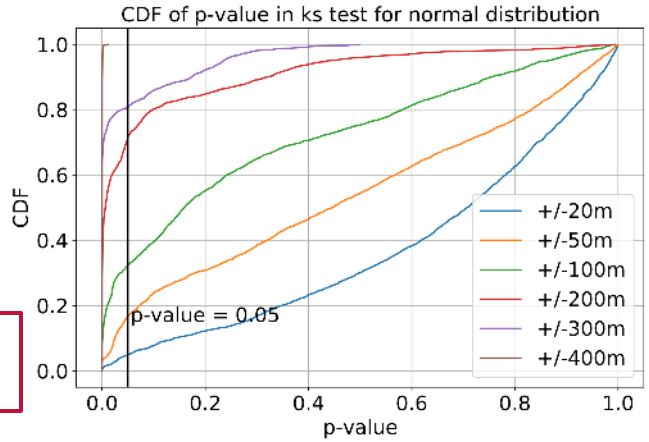


Apply Moving Average (sliding window)

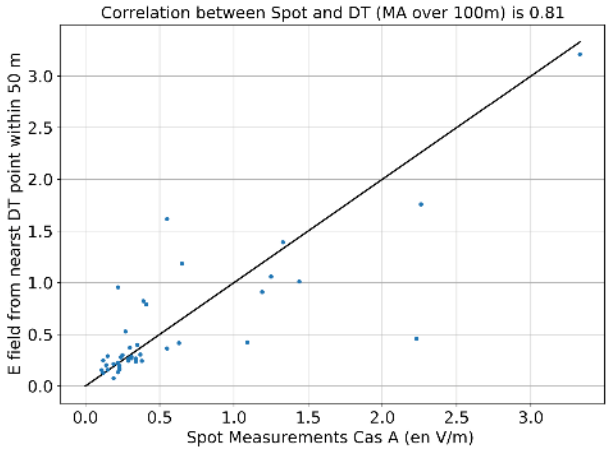
Data within one window:

- Perform KS test (Gaussian)
- Obtain p-value

*p < 0.05 → Reject null hypothesis
→ Significant difference



MA with window size: **100m**



- We compared the correlation between **E field** from each location of **spot** measurement and **nearest drive test** location.
- We observe a strong correlation between two cases.

*[1] **Wang, Shanshan**, et al., 2023 URSI GASS. IEEE, 2023.*

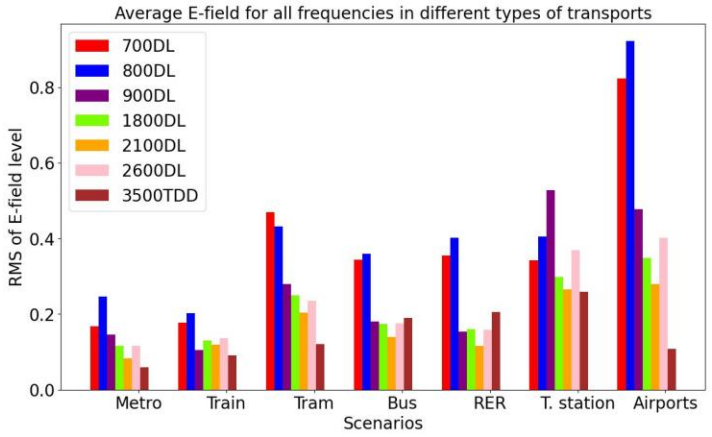
Supported by EU's Horizon Europe Framework Program under Grant N° 101057622 (SEAWave** Project).*

STATISTICAL ANALYSIS ON EMF EXPOSURE

Indoor + Downlink

MVG EME Spy Evolution

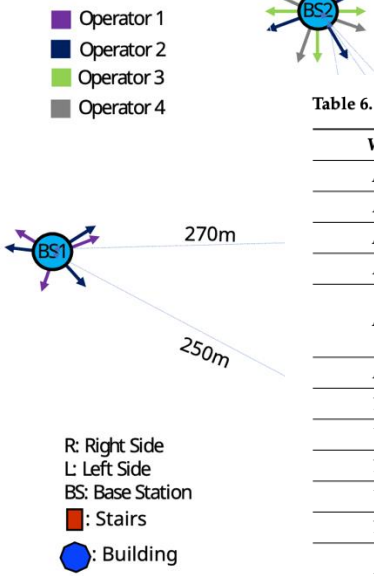
Public transports [1]*



K-means clustering using **4 moments**: $\{\mu_f, \sigma_f^2, S_f, K_f\}$ of **power density.**

	Results
Cluster 1	M3-6, 8, 11-14, RER E, line P, All trams (except T1), 5 buses, All train stations (except CDG), CDG airport
Cluster 2	M1, 2, 7, 9, 10, RER B, D, T1, 3 buses, Line H, CDG train station, Orly airport
Cluster 3	RER A, C

Indoor office buildings [2]



Narda NBM 550

Table 6. K-S Test checking the normality of exposure on all wings of building A, B, and C.

Wing	Type	Status	Test Statistic	*p*-Value
A0R	Corridor	Occupied	0.118	0.308
A0L	Corridor	Occupied	0.133	0.187
A1R	Corridor	Occupied	0.147	0.086
A1L	Corridor	Occupied	0.08	0.795
A2R	Corridor R Office L Office	Occupied Occupied Occupied	0.089 0.144 0.166	0.599 0.848 0.776
A2L	Corridor	Occupied	0.114	0.363
B0R	Corridor	Occupied	0.131	0.287
B0L	Corridor	Occupied	0.139	0.244
B1R	Corridor	Occupied	0.12	0.365
B1L	Corridor	Occupied	0.085	0.814
B2R	Corridor	Occupied	0.173	0.062
B2L	Corridor R Office L Office	Empty Empty Empty	0.138 0.248 0.114	0.25 0.235 0.932
C0R	Corridor	Occupied	0.091	0.991
C0L	Corridor	Occupied	0.173	0.078
C1R	Corridor	Occupied	0.104	0.507
C1L	Corridor	Occupied	0.089	0.656
C2R	Corridor	Occupied	0.106	0.498
C2L	Corridor R Office L Office	Empty Empty Empty	0.162 0.251 0.130	0.056 0.172 0.916

*p < 0.05 means
→ Reject null hypothesis
→ Significant difference

Gaussian distribution!

[1] Yarui Zhang, **Shanshan Wang**, et al., IEEE Access (2024).*
*[2] Mulugeta, Biruk Ashenafi, **Shanshan Wang***, et al., Sensors 23, no. 7 (2023): 3583.*

* Supported by EU's Horizon Europe Framework Program under Grant Nº 101057622 (**SEAWave** Project).

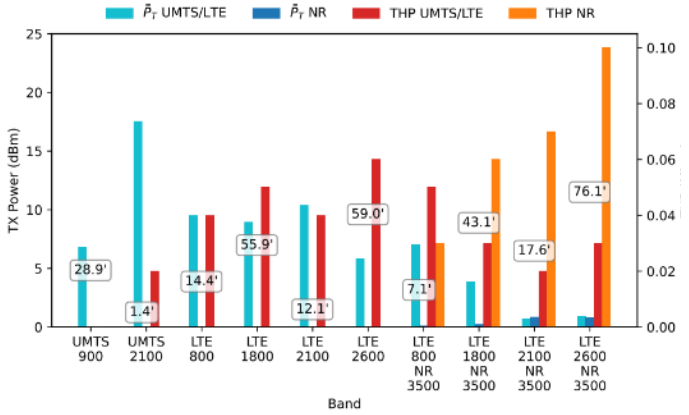
STATISTICAL ANALYSIS ON EMF EXPOSURE

Uplink

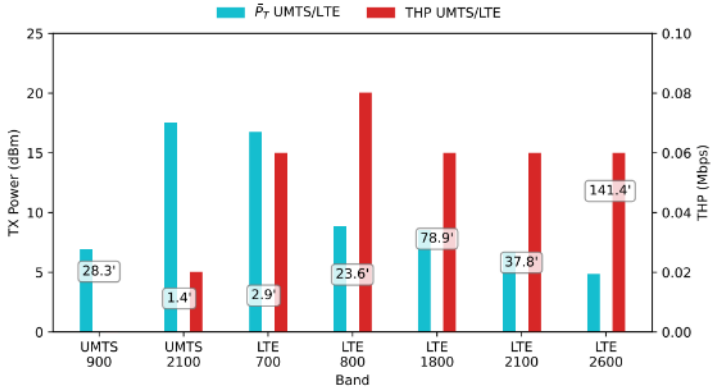
To Evaluate the transmit power:

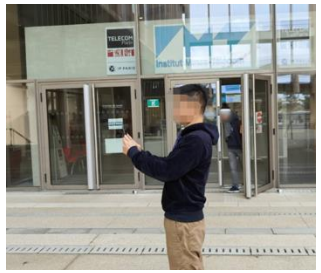
- In different locations (Num: 380)
  - universities,
  - streets,
  - train station,
  - shopping mall,
  - airport…
- For different services
  - Voice Call
  - WhatsApp Voice
  - WhatsApp Video
  - FTP Data Uploading
- 2G, 3G, 4G vs. 5G

VoIP-5G enabled

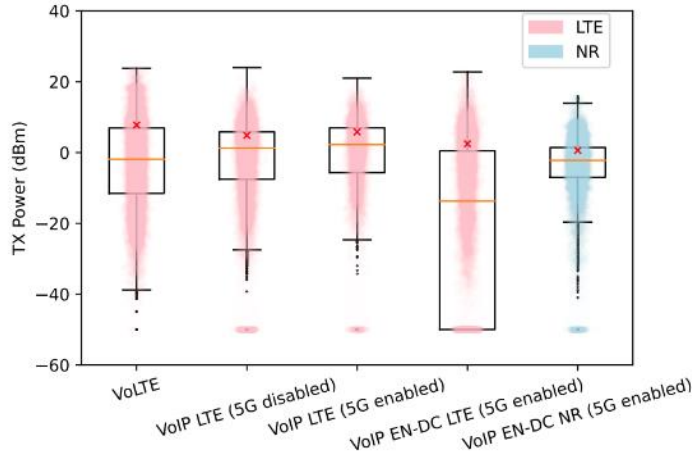


VoIP-5G disabled





LTE vs. 5G NR (Tx Power)



Same trend observed for other services

[1] Jiang Liu, et al., IEEE Access (2024).
* Supported by EU's Horizon Europe Framework Program under Grant Nº 101057622 (**SEAWave** Project).

STATISTICAL ANALYSIS ON EMF EXPOSURE

Uplink

REBT: radiated energy per bit transmitted

$$REBT = \frac{Transmitted\ Energy}{Transmitted\ bits} = \frac{P*T}{Data} = \frac{P_{tx}}{Throughput}$$

Service	5G	Tech	Time (min)	P_T (dBm)	NR P_T (dBm)	THP (Mbps)	NR THP (Mbps)	REBT (mJ/Mb)
VoCS and VoLTE	disabled	GSM	0.03	23.97	NA	0	NA	NA
		UMTS	48.1	9.32		0		
		LTE	330.58	8.62		0.03		242.33
VoIP	enabled	UMTS	30.28	8.51	NA	0	NA	NA
		LTE	141.39	8.16		0.05		131
		ENDC	143.87	2.48	0.61	0.03	0.08	26.55
	disabled	UMTS	29.69	8.60	NA	0	NA	NA
		LTE	284.57	7.16		0.06		86.67
Video	enabled	UMTS	3.63	19.79	NA	0.05	NA	1905
		LTE	113.16	13.58		0.54		42.22
		ENDC	199.14	8.51	4.67	0.36	0.38	13.55
	disabled	UMTS	3.49	19.79	NA	0.05	NA	1903.8
		LTE	313.36	11.82		0.57		26.67
FTP	enabled	UMTS	3.03	20.28	NA	0	NA	NA
		LTE	290.39	22.09		10.57		15.31
		ENDC	292.68	20.20	9.80	15.21	7.21	5.1
	disabled	UMTS	3.03	20.28	NA	0	NA	NA
		LTE	626.15	21.55		14.79		9.65

Compared with LTE, ENDC (5G) is more energy efficient.

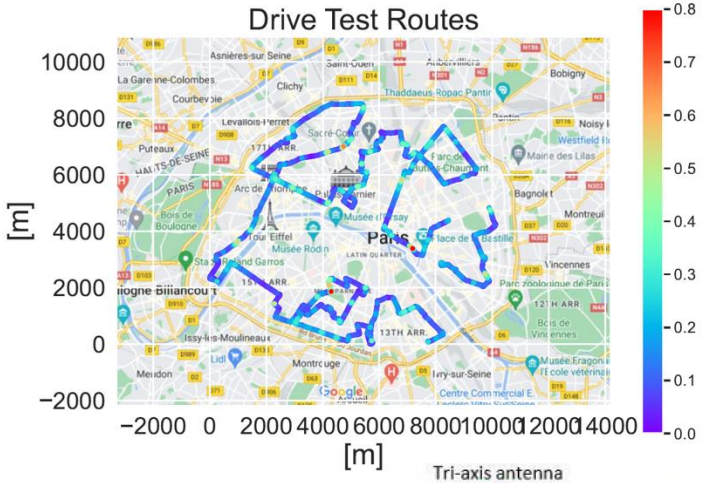
OUTLINE

- Introduction to EMF Exposure to Human Health
- Assessments of RF-EMF Exposure
- **AI methods-based prediction**
- Stochastic Modeling of Exposure
- Summary and Perspectives

AI-BASED PREDICTION ON RF-EMF EXPOSURE

Outdoor + Downlink

Prediction of RF-EMF exposure map

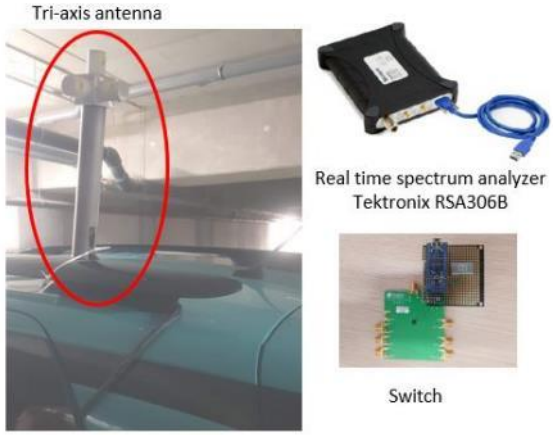


- Mobile App: *Geo Tracker*

- **Time (UTC)**
- **Coordinates (Lat, Lon)**

Equipment:

- Tektronix RSA306B
- 3-axis dipole antenna
- Switch
- Arduino



- **E Field** from Measures (MHz): 700, 800, 900, 1800, 2100, 2600, 3500

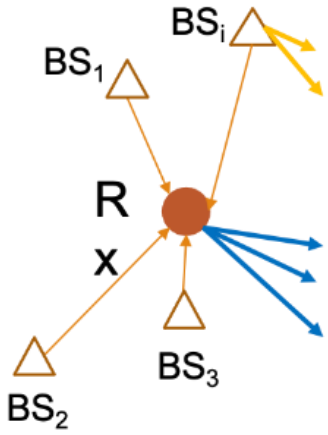
Frequency	E-Field (V/m)
10-400 MHz	28
0.4-2 GHz	$1.375\, f^{1/2}$
2-300 GHz	61

Eq900[2]

*[1] **Shanshan Wang** et al., Telecom. Vol. 3. No. 3. MDPI, 2022.*
[2] Wiart, J. Radio-frequency human exposure assessment: from deterministic to stochastic methods; John Wiley & Sons, 2016.

AI-BASED PREDICTION ON RF-EMF EXPOSURE

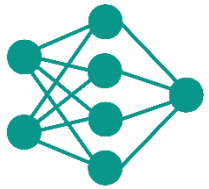
Outdoor + Downlink



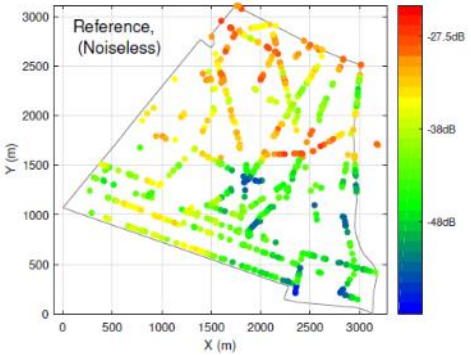
Features from BS_i:
- Distance d_{BS_i-user}
- Azimuth of antenna

Other Features :
- Time
- Location of the Rx

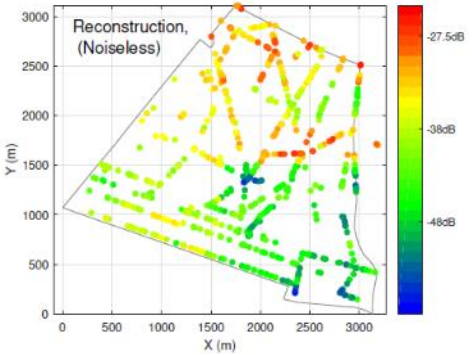
ANN Models



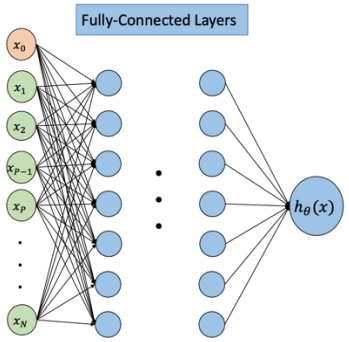
Reference



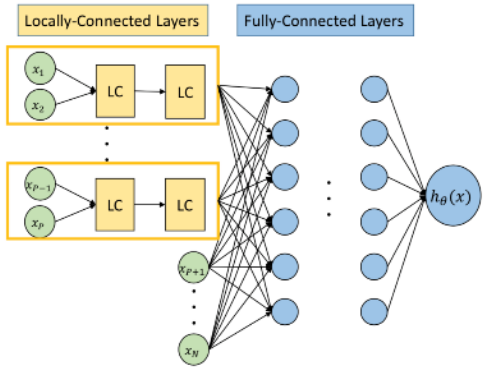
Reconstruction



Good agreement



Model (a)



Model (b)

N	Model (a)		Model (b)	
	R^2	MSE	R^2	MSE
3	0.66522	0.00148	0.805	0.000805
5	0.74810	0.00111	0.806985	0.00079
7	0.75016	0.0011	0.813376	0.000764

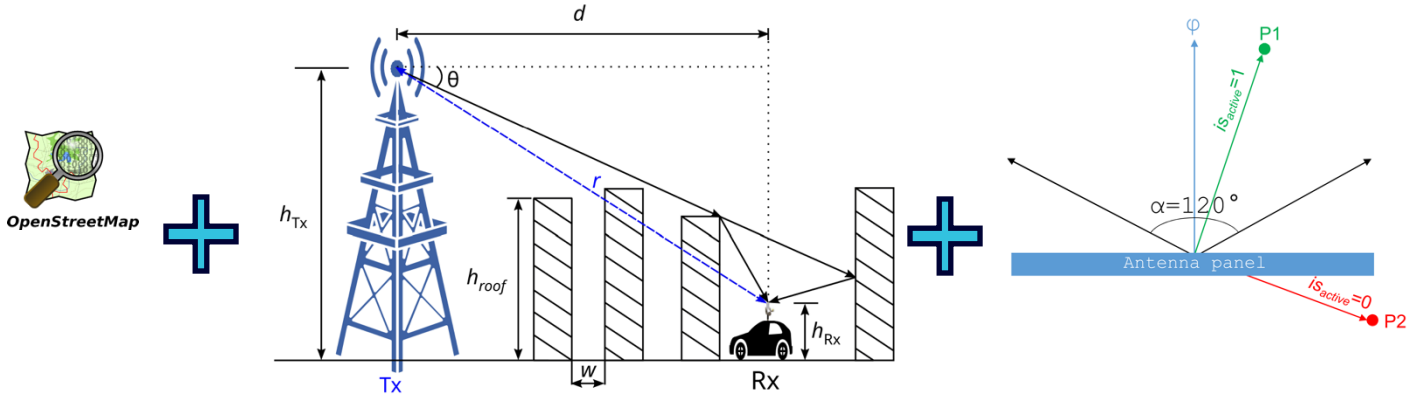
Interpolation?
or
Extrapolation?

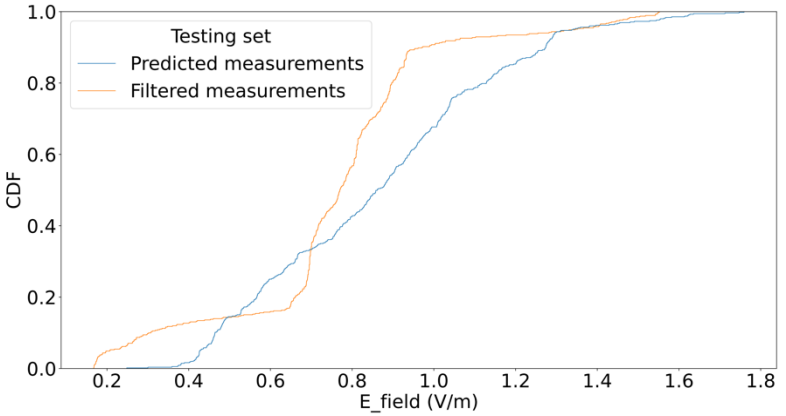
[1] ***Shanshan Wang***, *et a*

* Supported by **Beyond5G** Project.

AI-BASED PREDICTION ON RF-EMF EXPOSURE

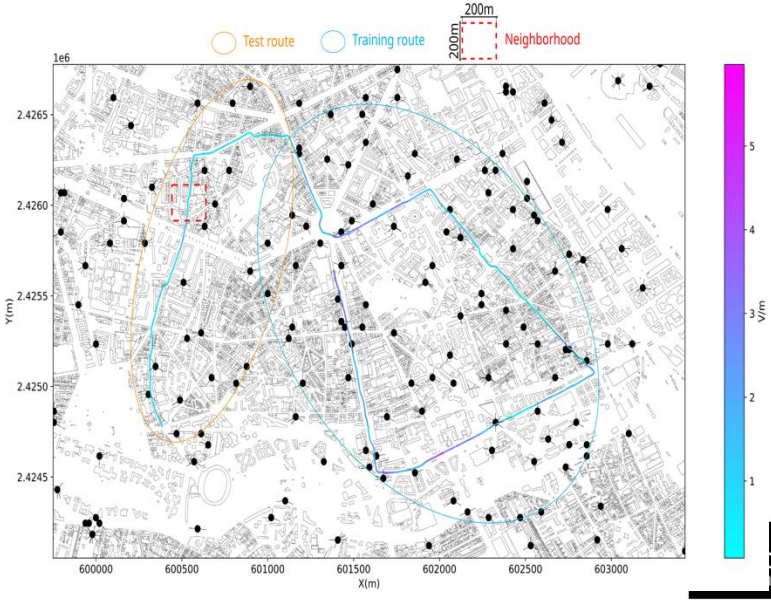
Outdoor + Downlink





Parameters for Cost 231-Walfisch Ikegami model.

Feature	Description
f_1	X
f_2	Y
f_3	Measurement hour
f_4	Density of surrounding buildings
f_5	Height of closest building
f_6	Distance to closest building
f_7	Number of active bands inside a circle centered at each MP with a radius of 160 m
f_8	Number of active antennas inside a circle centered at each MP with a radius of 160 m
$f_{9,\, i=\{1,\ldots,16\}}$	Distance to first 16 closest sites
$f_{10,\, i=\{1,\ldots,16\}}$	Average height of active antennas for the first 16 closest sites
$f_{11,\, i=\{1,\ldots,16\}}$	Number of active bands for the first 16 closest sites
$f_{12,\, i=\{1,\ldots,16\}}$	Number of active antennas for the first 16 closest sites



[1] Chikha, Wassim Ben, **Shanshan Wang**, et al. *IEEE Access* (2023).

* Supported by EU's Horizon Europe Framework Program under Grant Nº 101057622 (**SEAWave** Project).

AI-BASED PREDICTION ON RF-EMF EXPOSURE

Some ongoing works:

1. Use CNN model to learn environmental parameters
   - Intelligently learn from the city structures
   - No need to manually processing propagation parameters

2. To quantify the uncertainty come from various aspects:
   - Dynamic radio environment;
   - Simultaneous traffic load from the base station;
   - Performance of measurement device due to temperature, humidity, and other environmental conditions;
   - Uncertainty from the in-sample and out-of-sample prediction.

OUTLINE

- Introduction to EMF Exposure to Human Health
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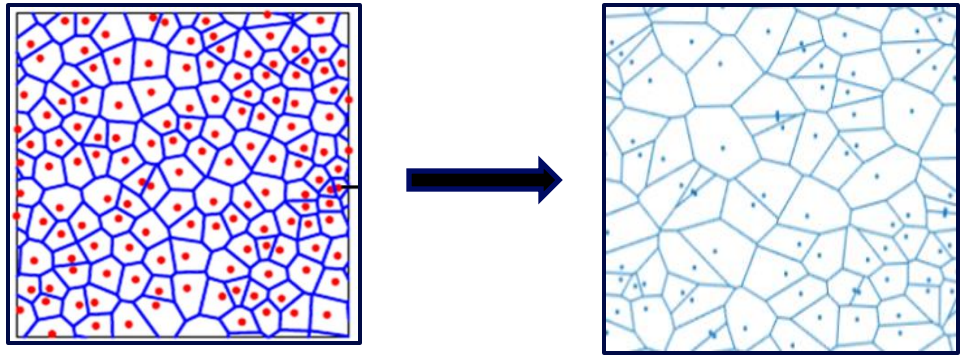
- **Stochastic Modeling of Exposure**
- Summary and Perspectives

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



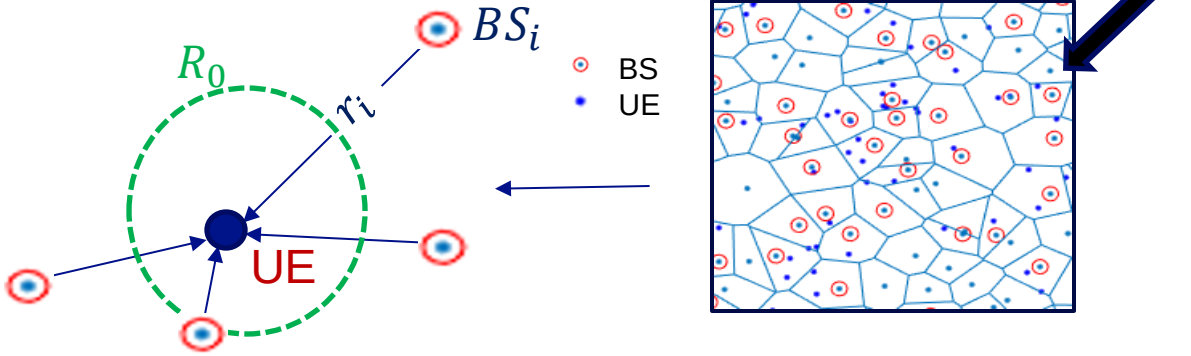
Actual 4G network

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

STOCHASTIC MODELING OF EXPOSURE

Maximize coverage vs. minimize EMF exposure?

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

System Model:

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

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

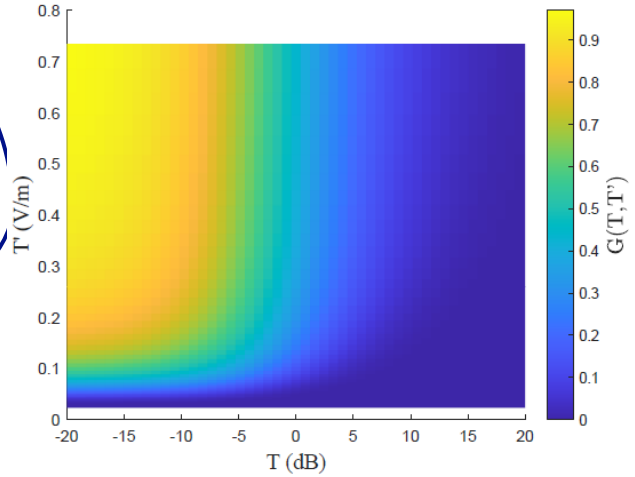
Realistic BS database:

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

$\beta-\text{GPP}$

I-PPP with a radial intensity measure

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



Brussel LTE 1800 MHz I-PPP

[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

CHARACTERIZATION OF EMF EXPOSURE

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

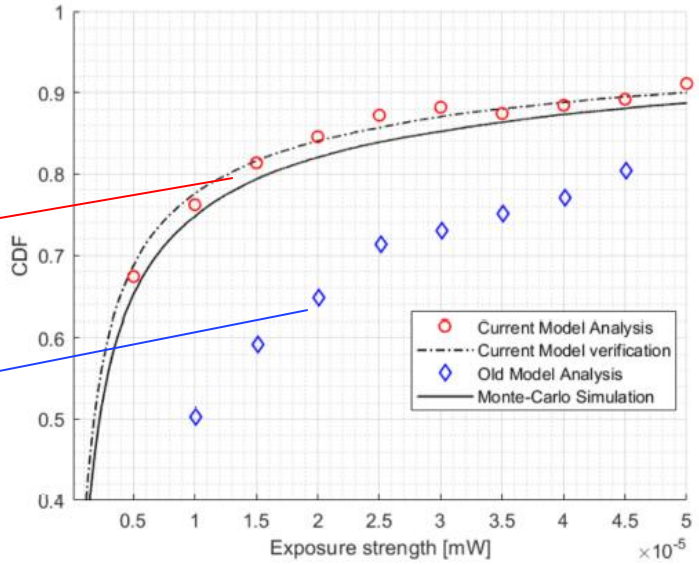
- Massive MIMO
- Digital Beamforming
- Single User
- NYUSIM Simulator

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

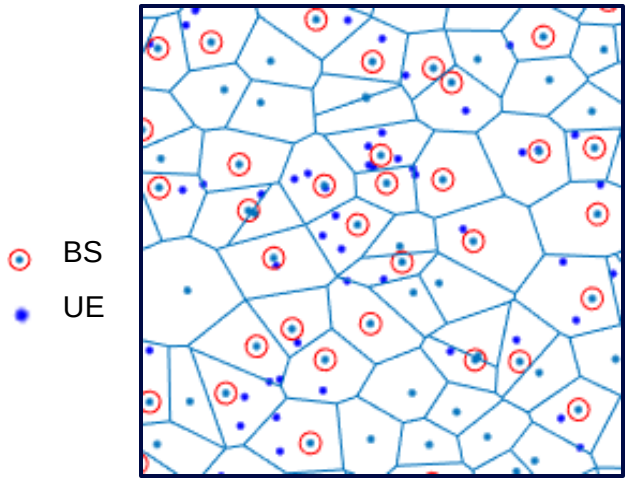
- Downlink multi-cell, multi-user massive MIMO network
- BSs and UEs modeled as PPPs Φ_{BS} and BPP Φ_{UE} on $\mathbb{R}^2$
- Large scale fading (BS_l and MT_k): $\beta_{lk}(R_{lk}) = \max(d, R_{lk})^{-\alpha}$
- Small scale fading: $h_{lk} \sim \mathcal{CN}(0, I_M)$, i.i.d. Rayleigh fading
- Precoding: 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

Average multi-user interference

Average inter-cell interference



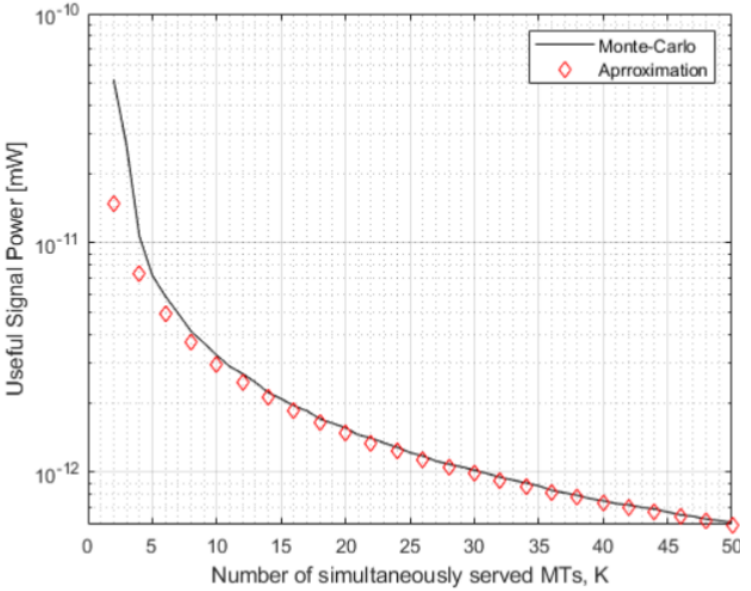
Φ_{BS} and Φ_{UE}

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



Average signal power to verify validity of the approximation $S = \rho_{dl}\mathbb{E}[\eta_{l0}\beta_{l0}^{S}]$

➢ **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 $\left(\beta_{lk'}^{S}\right)^{-1}$

STOCHASTIC MODELING OF EXPOSURE

Derivation of The Average Power Received

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

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

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

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

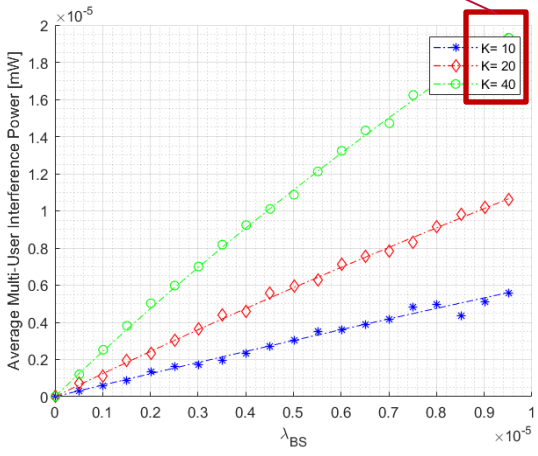
STOCHASTIC MODELING OF EXPOSURE

Numerical Results – Average Power

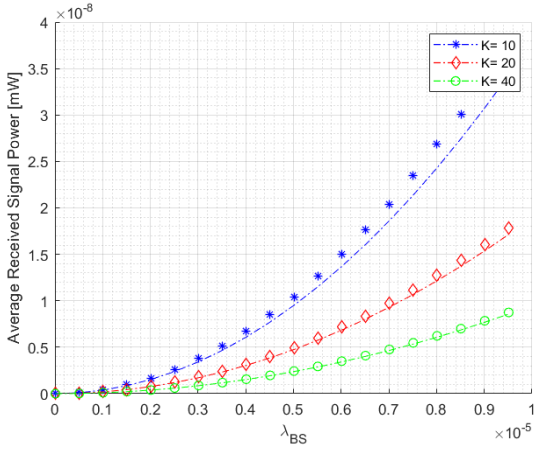
Number of Served UEs

Lines: Analytical Framework

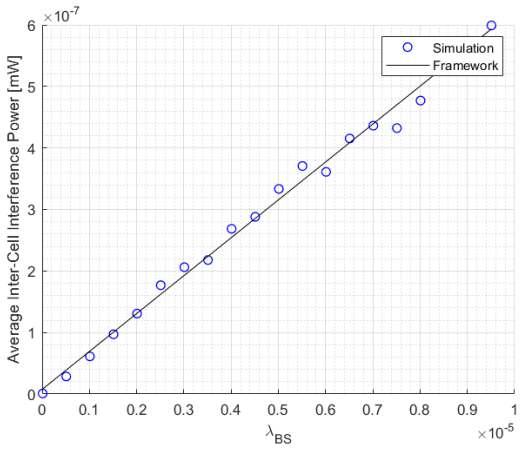
Markers: Monte-Carlo



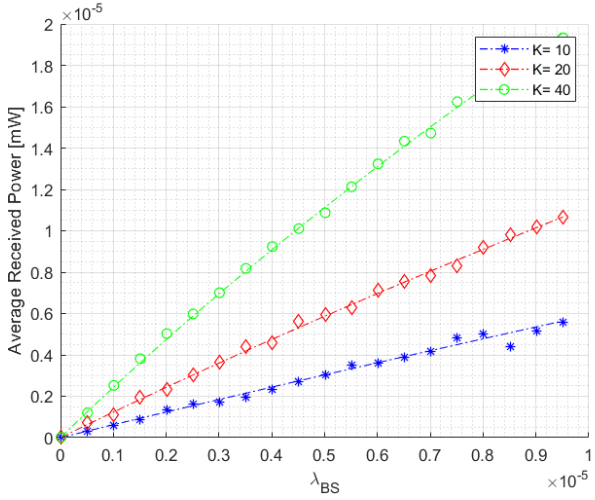
(a) Multi-user interference



(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.

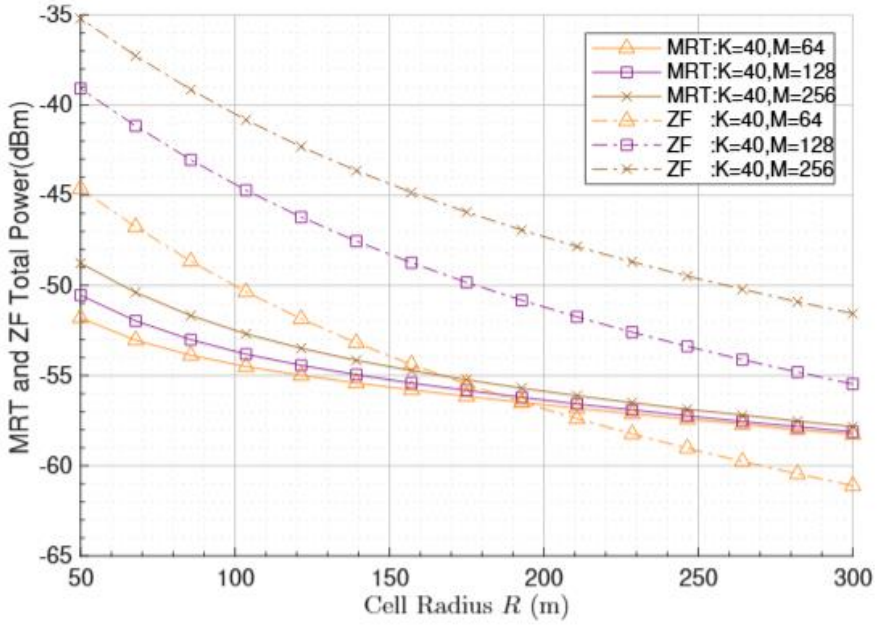
STOCHASTIC MODELING OF EXPOSURE

MRT vs. ZF

$$\mathcal{E}_{l0}^{\mathrm{mrt}} = M\rho_{\mathrm{dl}}\frac{1+\rho_{\mathrm{dl}}\mathbb{E}\left[\beta_{l1}^{l(s)}\right]}{K\left(\rho_{\mathrm{dl}}+\mathbb{E}\left[\beta_{lk}^{l-1}\right]\right)} + \rho_{\mathrm{dl}}\mathbb{E}\left[\sum_{l'\in\Phi_{BS}/\{l\}}\beta_{l1}^{l'(s)}\right] + \rho_{\mathrm{dl}}\left(\mathbb{E}\left[\beta_{l1}^{l(s)}\right] - \frac{1+\rho_{\mathrm{dl}}\mathbb{E}\left[\beta_{l1}^{l(s)}\right]}{K\left(\rho_{\mathrm{dl}}+\mathbb{E}\left[\beta_{lk}^{l-1}\right]\right)}\right)$$

$$\mathcal{E}_{l0}^{\mathrm{zf}} = (M-K)\rho_{\mathrm{dl}}\frac{1}{\mathbb{E}\left[\beta_{lk}^{l-1}\right]} + \rho_{\mathrm{dl}}\mathbb{E}\left[\sum_{l'\in\Phi_{BS}/\{l\}}\beta_{l1}^{l'(s)}\right]$$

Comparison of the average total power received by MT_0 under MRT and ZF precoding schemes versus cell radius with different number of antenna M.



[1] Jiangbo Wang, **Shanshan Wang**, and Hajar El Hassani. Submitted to WiOpt, 2024.

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SUMMARY AND PERSPECTIVES

Summary:

- Actual EMF exposure can be measured, characterized, monitored from deployed networks
- Artificial neural networks can be used to to predict EMF exposure.
- Stochastic model EMF exposure can be done for both current and future networks

Perspectives:

- EMF-aware design of networks are integrated with more emerging techniques, such as
  - Integrated sensing and communications (ISAC)
  - Reconfigurable intelligent surface (RIS)
- How to quantify the uncertainty in the EMF exposure predictions using AI means.