Spatio-Temporal Modelling of Urban 5G Downlink Exposure of Users and Non-users by Ray-Tracing

Matthias Leeman[1,] , Robin Wydaeghe[1,], Jeroen Van Der Straeten[1], Samuel Goegebeur[1], Günter Vermeeren[1,], and Wout Joseph[1,]
[1]WAVES, Department of Information Technology, Ghent University/IMEC, Ghent, Belgium
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Summary

In 5G networks, base stations dynamically form directional beams toward users, coupling the spatial and temporal variations of electromagnetic field exposure. We propose a novel spatio-temporal method that incorporates both active users and non-users in realistic 5G exposure simulations. Unlike prior studies that focus mainly on static scenarios, or dynamic settings without accounting for precoding effects, our work integrates precoding techniques with dynamic users. In addition, this work also provides a comprehensive comparison of exposure levels for users and non-users. The results show that users experience 5.2 dB to 3.7 dB higher field strengths for 8×8 antenna arrays compared to 4×4 arrays. Non-users also experience increased exposure, with median differences up to 2.4 dB. Importantly, all exposure levels remain well below 4% of the ICNIRP guidelines, even under maximum antenna power.

Introduction

The fifth generation (5G) of cellular networks is becoming ubiquitous in daily life [1]. To increase spectral efficiency,5G introduces beamforming as a core technology [2]. This is enabled by Massive Multiple-Input Multiple-Output (MaMIMO) base stations (BSs) directing electromagnetic energy towards active users [3]. To increase data rates, the operating frequency is increased from 4G's typical range of 0.7 GHz to 2.6 GHz to 3.5 GHz or 28 GHz to explore unlicensed GHz-sized bandwidths.

Currently, research on human exposure to electromagnetic fields (EMFs) mainly consists of constructing spatial and temporal models in different micro-environments [4]. However, because of the dynamic nature of user movement and active beamforming over time, the spatial distribution of EMFs changes over time [5]. In addition, the number of users also changes throughout the day and throughout the year, introducing a macro-temporal component in exposure assessment [6]. Consequently, a complete assessment of human exposure in 5G networks necessitates a combined analysis of spatial and temporal variations in EMF distributions. This highlights the need for a coupled spatio-temporal model based on a deterministic framework, given the significant influence of environmental features on exposure outcomes.

Therefore, this work offers insights into 5G exposure on a city-wide scale by integrating an agent-based model (ABM) into ray-tracing (RT) simulations. Maximum ratio transmission (MRT) precoding is implemented and evaluated. In addition, the influence of the antenna configurations (number of antenna elements) and user count on exposure is quantified. This offers a novel framework for evaluating exposure of moving pedestrians in city-scale environments.

Methods

Configuration

Terrain data, building data and BS information are loaded in MATLAB to perform RT. For each BS antenna, a 5G antenna array is generated. Both 4×4 and 8×8 antenna arrays are investigated. Cross-polarized elements are used with half-wavelength spacing. Finally, the exposure for both users and non-users is evaluated using an isotropic receiver (Rx) antenna positioned 1.5 m above the ground.

Agent-based model for pedestrians

The generated agents of the ABM represent pedestrians walking in the environment. These agents include both *users*, that actively engage with the 5G network, and *non-users*. Several assumptions are made in this model:

- All agents are pedestrians.
- The agents move from building to building (starting point and destination outside a building).
- The agents move with a constant speed of 5 km/h.
- The agents do not deviate from the optimal path between starting point and destination.
- When the agents reach their destination within the simulated time interval, they return to their respective starting points. For the duration of the simulation, the agents will go back-and-forth from starting point to their destination point.

For each agent, a starting point and end point are determined based on population density. The optimal path is generated between the starting point and end point resulting in a walked path for each agent. The agents are randomly assigned as either users or non-users at the start of the simulation. Once assigned, users and non-users maintain their respective roles throughout the entire simulation duration. The exposure is highly dependent on the specific agent paths within a scenario. Therefore, multiple distinct sets of agent trajectories are generated. This way, a more comprehensive stochastic analysis is achieved based on the probabilistic behaviours (based on population density) of users and non-users. This approach ensures that the results are not dependent on a single set of agent paths but represent the average exposure across multiple possible scenarios.

Modelling

For each time step, the analysis consists of two steps. First, all potential serving antennas are determined for each user. The potential antennas are located within a 1 km radius of the user. The maximum azimuthal angle between the antenna and the user is 90°, ensuring that the antenna exclusively serves users within its forward-facing coverage area. RT is performed using MATLAB between these potential serving antennas and their corresponding users. The output of the ray-tracer includes the pathloss (PL) in dB, angle-of-departure (AoD) and phase shift ($\Delta\varphi$) of each ray. From these outputs the electric field is calculated as a post-processing step.

Results

Influence of antenna array configuration and user count

Table 1 lists the median electric field strengths and interquartile ranges (IQRs) for various scenarios involving different antenna array configurations and precoding schemes. A general decline in user field strength is observed with increasing user count. This is expected, as the total transmitter power for each antenna is split over its served users.

The decline in user field strengths with increasing numbers of users is dependent on the antenna array configuration. Specifically, as the number of users rises from 10 to 50, the median field strength decreases by 0.5 dB for a 4×4 antenna array and by 2.0 dB for an 8×8 antenna array. These findings indicate that larger antenna arrays experience a more pronounced reduction in individual user field strength as user count increases. This phenomenon can be attributed to the more uniform exposure distribution characteristic of smaller antenna arrays, even at lower user counts. In contrast, as the number of users grows, the exposure distribution of larger antenna arrays progressively becomes more uniform, leading to a greater decrease in individual user field strengths. Despite this larger reduction with user count, the field strengths are consistently higher for the 8×8 configuration. As the user count

Table 1: Summary of electric field strength results for the multi-user scenarios. The median electric field strength (and interquartile range) for users and non-users are presented for across the different scenario configurations with 50 non-users.

		Median Electric Field Strength (and IQR) [V/m]	
Number of users	Antenna array	Users	Non-users
10	4 x 4 8 x 8	0.92 [1.30] 1.68 [2.25]	0.61 [1.00] 0.73 [1.39]
20	4 x 4 8 x 8	0.92 [2.25] 1.56 [2.00]	0.70 [1.05] 0.89 [1.51]
30	4 x 4 8 x 8	0.89 [1.21] 1.42 [1.88]	0.72 [1.07] 0.93 [1.51]
40	4 x 4 8 x 8	0.87 [1.19] 1.37 [1.84]	0.74 [1.07] 0.99 [1.56]
50	4 x 4 8 x 8	0.87 [1.19] 1.33 [1.79]	0.77 [1.11] 1.01 [1.58]

rises, a diminished impact of the antenna array size is observed: for 10 users, the field strength difference between the two configurations is 5.2 dB, while for 50 users, it decreases to 3.7 dB.

For non-users, Table 1 shows that the decline in field strengths is less sensitive to the antenna configuration than for users. However, the exposure values remain generally higher for larger antenna arrays. As the number of users increases from 10 to 50, the median field strengths for non-users increase by 2.0 dB for the 4×4 array and 2.8 dB for the 8×8 array. The field strength difference between the two configurations is 1.6 dB for 10 users and increases to 2.4 dB for 50 users. For an 8×8 antenna, one would expect a lower median field strength for non-users, since the beams are more directional towards the user positions. However, the results suggest that, with an ABM based on population density and random user selection, non-user field strengths are also higher for an 8×8 array compared to a 4×4 array. This can be attributed to the fact that the users are stochastically close to users. Therefore, the non-user field strengths are also higher for the 8×8 array.

The IQRs for user field strengths also exhibit a reduction of 0.8 dB and 2.0 dB for the 4×4 and 8×8 configurations, respectively, as the user count increases from 10 to 50. Similar to the median values, the IQRs are higher for 8 × 8 configurations, with average differences of 4.8 dB and 3.5 dB observed for 10 and 50 users, respectively. This indicates that users with high signal strength benefit more from the enhanced beamforming capabilities of the 8×8 array than users with lower signal strength, causing greater variability in exposure levels. In addition, the results also show that users with higher exposure are impacted more by increasing users count than users with lower exposure.

The IQRs for non-users decrease by 0.9 dB and 1.1 dB for the 4×4 and 8×8 configurations, respectively, as the number of users increases from 10 to 50. However, the IQRs are consistently higher for the 8×8 configuration, with average differences of 2.9 dB and 3.1 dB for 10 and 50 users, respectively. These findings highlight that the user count influences non-user field strengths more than the number of antenna elements do. In addition, the number of antenna elements has a more substantial impact on user field strengths than on non-user field strengths.

Comparison with ICNRIP reference value

Figure 1 presents the maximum exposure values across all iterations of each scenario, expressed as a ratio relative to the ICNIRP reference value. These values represent the theoretical worst-case scenario for a specific number of users within the study area, providing valuable insights into the potential

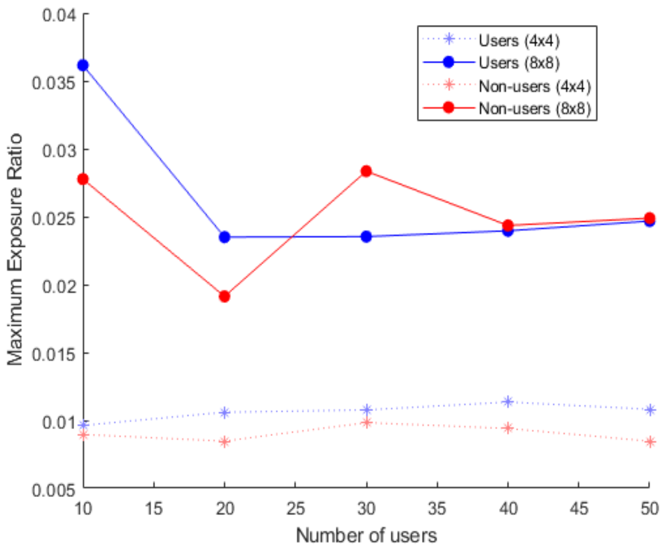

Figure 1: Maximum exposure evaluation. The maximum exposure ratio compared to ICNIRP reference values for users and non-users as function of number of users. The highest observed exposure is below 4% of the ICNIRP reference value.

maximum exposure levels under high BS power conditions. The results demonstrate that maximum exposure levels across all configurations remain well below the ICNIRP guidelines for the general public, ensuring that maximum exposures comply with established health guidelines. The maximum exposure ratio is less than 4% over all scenarios and configurations The maximum exposure levels exhibit no significant correlation with the number of active users. This outcome likely arises from the calculation of maximum values across multiple iterations, where absolute maxima are determined by the specific spatial arrangements in each iteration. In certain scenarios, a cluster of users may lead to elevated exposure levels due to interference, despite the distribution of transmit power among a larger user base.

Conclusions

The results demonstrate that an 8×8 antenna array results in 5.2 dB to 3.7 dB higher field strengths compared to an 4 × 4 array, depending on the number of active users. In addition, non-user exposure also increases with larger antenna arrays, with differences of up to 2.4 dB. Moreover, the analysis of maximum exposure levels relative to the ICNIRP limit show that even in the worst-case scenarios, the maximum observed exposure remains well below 4% of the ICNIRP reference level for the general public.

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