**S01-5 [11:30]**

# Numerical assessment of the spatiotemporal duty cycle of 5G Massive MIMO in an outdoor urban environment using radio-frequency Ray-Tracing

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This work presents a numerical method of estimation a realistic time-averaged antenna array pattern of a massive MIMO base station (BS). The Ray-Tracing is used to calculate the propagation in a large number of stochastically generated environments modelling an outdoor urban scenario. The antenna patterns are averaged over a 6 and 30 minute intervals and evaluated for varying number of the BS antennas and active users, as well as different transmit precoding/beamforming schemes. It is shown that the realistic average maximum gain can be as low as 6% of the theoretical maximum when the interference-cancelling Massive MIMO precoding, and around 13% in case of a codebook beamforming, measured as a 95th percentile of the sample distribution.

## Introduction

Massive multiple-input multiple-output (MIMO) has become one of the most promising fifth generation (5G) technologies in recent years. Simultaneous utilization of a large number of antenna elements at the base station (BS) compared to the number of served users brings a record performance in terms of throughput and power efficiency as shown in theoretical predictions [3] and demonstrated in test-bed measurements [2]. The BS estimates the wireless channels of the user equipment (UE) devices in real time using the pilot sequences transmitted in the uplink (UL). The knowledge of the channel allows the BS to perform the downlink (DL) precoding or select an optimal beam out of a predefined set in case of the codebook beamforming operation. High array gains and narrow beams produced by the the BS allow to simultaneously transmit to multiple UEs sharing frequency resources in the Time-Division Duplexing (TDD) mode. Human electromagnetic field (EMF) exposure in the far-field region of a transmitter is approximately proportional to the transmitter antenna gain.

When assessed the EMF exposure has to be averaged over a time period standardized by the International Commission on Non-Ionizing Radiation (ICNIRP). In the latest version of the ICNIRP guidelines the averaging time duration is set to 30 minutes [8], and the older, still widely referred to, version specified a 6 minute interval [9]. In a typical 5G scenario, the UEs receive the DL traffic in short (hundreds of milliseconds) bursts. Users entering and leaving the network within the averaging interval cause the time-average BS array radiation pattern to drop below the theoretical maximum, that otherwise would be realised if continuously transmitting a fixed broadside beam. In recent publications different numerical approaches were utilized to estimate how much a realistic maximum time-average array gain could be lower than its theoretical maximum.

In [6] several analytical UE distributions within a single wireless cell were investigated, while another analytical queue model described the number of the UEs independently joining and leaving the service. The codebook beamforming in both azimuth and elevation was performed by the BS, modelled as a square array of up to 15-by-15 antenna elements. In [1] the reciprocity-based Maximum Ratio Transmission (MRT) was implemented at the BS and the 3GPP channel model was used for the UE scheduling. In [7] several realistic multi-column BS antenna arrays capable of the codebook beamforming only in azimuth were studied using a Poisson process for the UE queuing. In this contribution we compare the codebook beamforming with two reciprocity-based precoding schemes, MRT and Zero-Forcing (ZF), in therms of the maximum time-averaged gain of a BS implementing these transmission strategies. The ZF precoding aims at reducing the inter-UE interference and is expected to be used in many practical setups. The Ray-Tracing (RT) method was used to simulate site-specific wireless channel in an outdoor urban macrocell, for which the geometry is generated stochastically based on small set of parameters. The TDD DL duty cycle of 75% is often taken as a realistic estimate [1, 6, 7], but is not accounted for in the results reported in this contribution. An arbitrary TDD duty cycle can be applied to the values presented below by scaling them down using a desired factor.

## Materials and methods

The outdoor macrocell model used for propagation prediction is shown at Figure 1. The area is contained within a 100m-by-100m square. The terrain is modelled as a flat plane, on which building blocks of cuboidal shape are placed. The size and location of the blocks are calculated stochastically as follows:

1. The blocks are arranged on a rectilinear grid in the horizontal plane.
2. The block height has a uniform random distribution from 5 m to 20 m.
3. The block side length has a uniform random distribution from 15 m to 25 m.
4. The distance between blocks in the x and y direction in selected independently with equal probability as 10 m, 15 m or 20 m.

A single BS is located at a fixed height of 25 m at the of one of the sides of the area boundary. The BS consists of 100 dipole antenna elements forming a 10-by-10 square array with the inter-element spacing of 0.5 wavelength at 3.5 GHz. The BS is tilted down by 30 degrees and 120 degrees in azimuth and 30 degrees in elevation, which approximately corresponds to the BS parameters used in [6]. The UEs are distributed a horizontal rectilinear grid at a fixed 1.5 m height above the ground within the area of the BS coverage and outside of the building blocks. The UE grid spacing is uniform throughout the are and equals to 2 m in x and y directions. In total 25 environment samples were generated using the procedure outlined above and simulated using the RT method. For each UE in the simulation the output is a set of rays, which originate at the BS and are traced through the environment according to the ray-optics approximation augmented with the uniform theory of diffraction (UTD). Reflections, transmissions, and diffractions are calculated for all launched rays and the rays that reach at least one of the UEs are saved as the RT output. Taking the rays' superposition at each UE while keeping track from which BS element each ray is launched, the wireless channel matrix is calculated. For a more detailed description of the massive MIMO channel modelling using the RT method, see [5]. The channel matrix is directly used to calculate the BS array transmission weights of the MRT or ZF precoding scheme [4]. To simulate a BS operating in the beamforming mode, a grid of 32 beams in azimuth and 8 beams in elevation was defined with a fixed set of the transmit weights. The RT-calculated channel matrix is then used to select a beam producing the highest signal at a target UE.

## Results

Figure 2 shows a table of the 95th percentiles of the 6-minute average gain fraction of the theoretical maximum taken over 2500 independent average gain evaluations. In general, the more UEs are connected at a time (K), the lower the time-average average gain if either MRT or ZF precoding scheme is used at the BS. With beamforming, larger UE counts lead to an increase of the time-average gain for small BS antenna counts (N = 4, 16) and short UE connection duration (T = 1 s, 10 s) as seen in Figure 2. For a realistic configuration with N = 64 antenna elements, all studied transmit schemes showed nearly equal largest time-average gain value of around 0.46 with K = 1 active UE and the longest of studied UE connection times T = 60 s. With N = 64, CB and MRT also have nearly equal lowest values of 0.16 and 0.18, respectively. For the same parameter configuration ZF shows a much lower minimum of around 0.08, which means that the maximum time-average gain falls below one tenth of the theoretical maximum in 95% of all obtained samples. When using MRT or ZF, increasing BS antenna and UE counts, and decreasing the connection time leads to a decrease in the time-average gain. Accordingly, the lowest overall MRT and ZF values were 0.14 and 0.06 for N = 100, K = 10 with the UE connection time of 1 s.

Figure 3 shows a table analogous to the one in Figure 2, but for which the 30 minute averaging interval was used and includes only CB and MRT schemes. The maximum gain averaged over a longer time was found to be no greater than the one averaged over a shorter period. This was expected, as over a longer time period a larger number of independent realizations of the BS array radiation pattern are averaged, decreasing the maximum. Indeed, with N = 64, its 95th percentile drops to 0.23 and 0.25 for CB and MRT, respectively for K = 1 and T = 60 s. However, for shorter connection times (T = 1 s, 10 s) and larger UE counts (K > 5), no significant difference was found. This indicates that for realistic system parameters taking a 6 minute average might be sufficient when assessing human EMF exposure.

## Conclusions

The presented findings show that for a realistic system model in which the BS is a 64-element antenna array, the maximum 6 minute averaged BS gain is at least twice lower compared to its theoretical maximum (not taking the TDD duty cycle into account).
For short UE connection times the average gain decreases down to around 0.2 with MRT and CB and as low as 0.08 with ZF.
Increasing the averaging time always decreases the average gain, however for shorter of studied connection times and larger active UEs counts this effect was not significant.

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## Figures

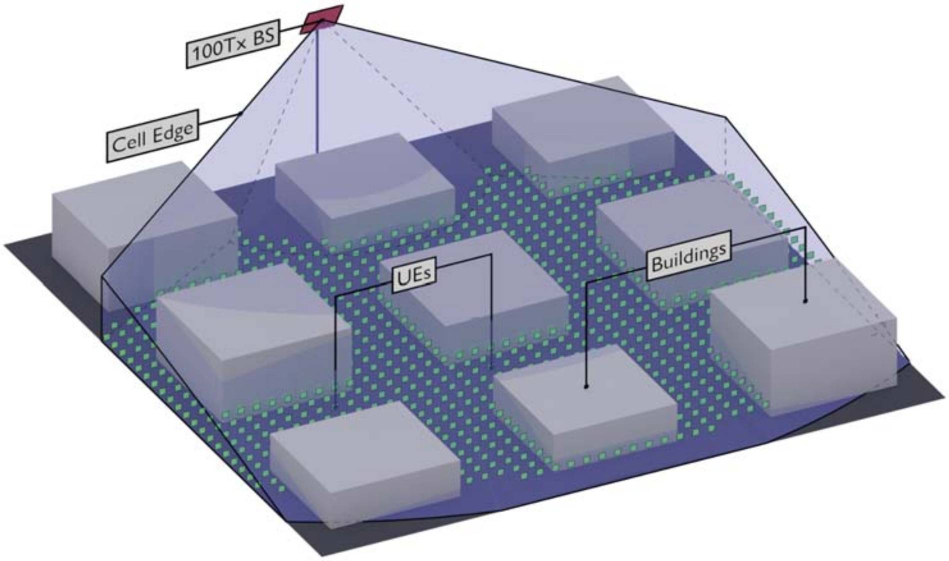
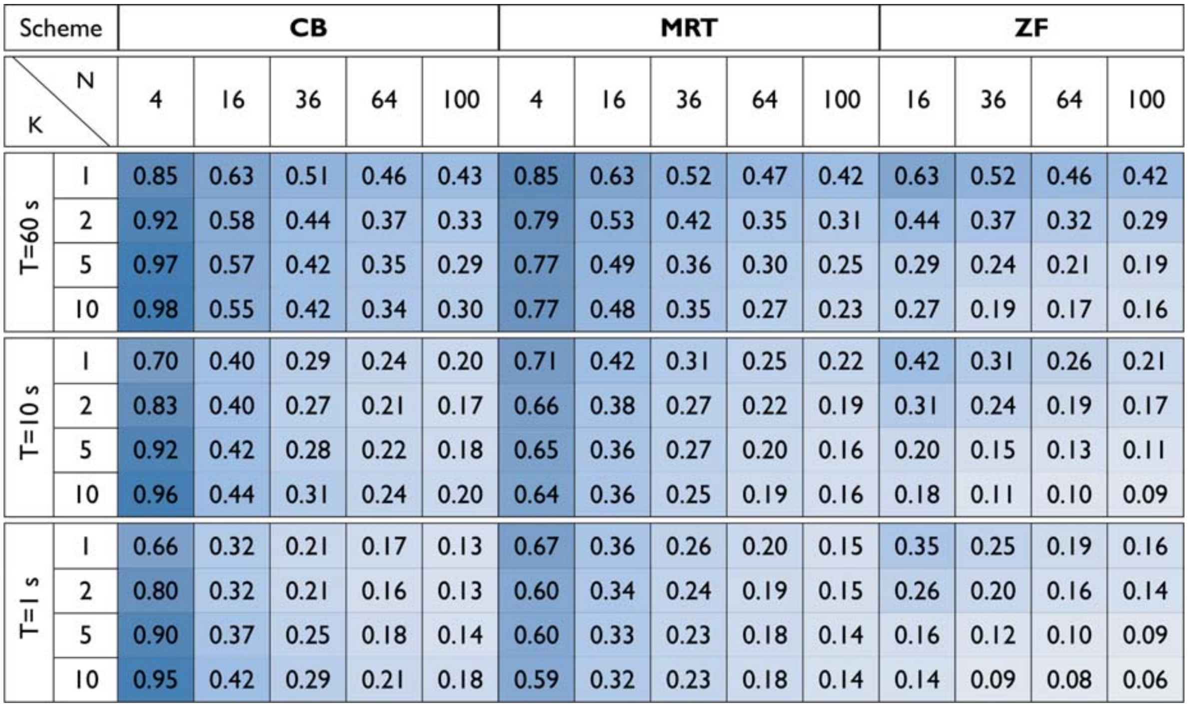
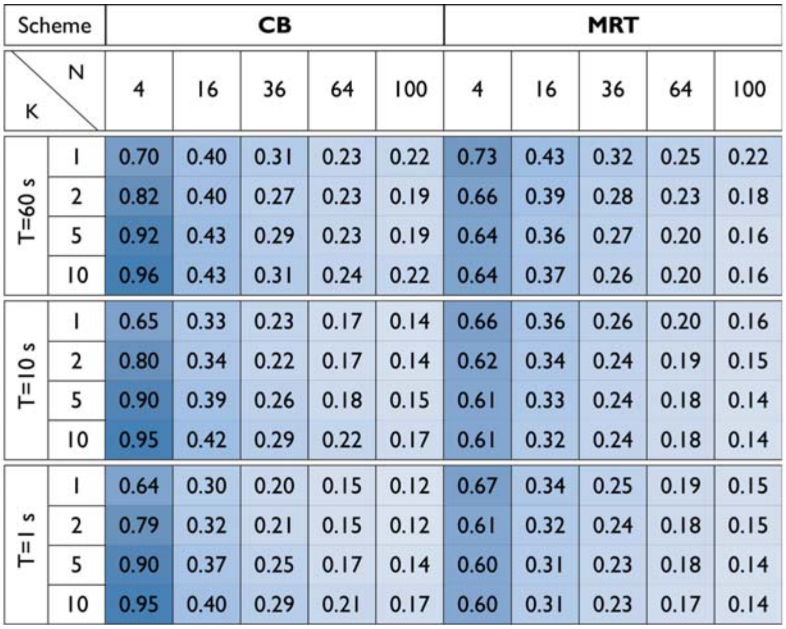


Figure 1. An outdoor urban macrocell model sample. The boundary of the cell is shown with a dark blue color, the BS, UEs and bulding blocks are labeled.



| Scheme | | CB | | | | | MRT | | | | | ZF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K \ N | | 4 | 16 | 36 | 64 | 100 | 4 | 16 | 36 | 64 | 100 | 16 | 36 | 64 | 100 |
| T=60 s | 1 | 0.85 | 0.63 | 0.51 | 0.46 | 0.43 | 0.85 | 0.63 | 0.52 | 0.47 | 0.42 | 0.63 | 0.52 | 0.46 | 0.42 |
| | 2 | 0.92 | 0.58 | 0.44 | 0.37 | 0.33 | 0.79 | 0.53 | 0.42 | 0.35 | 0.31 | 0.44 | 0.37 | 0.32 | 0.29 |
| | 5 | 0.97 | 0.57 | 0.42 | 0.35 | 0.29 | 0.77 | 0.49 | 0.36 | 0.30 | 0.25 | 0.29 | 0.24 | 0.21 | 0.19 |
| | 10 | 0.98 | 0.55 | 0.42 | 0.34 | 0.30 | 0.77 | 0.48 | 0.35 | 0.27 | 0.23 | 0.27 | 0.19 | 0.17 | 0.16 |
| T=10 s | 1 | 0.70 | 0.40 | 0.29 | 0.24 | 0.20 | 0.71 | 0.42 | 0.31 | 0.25 | 0.22 | 0.42 | 0.31 | 0.26 | 0.21 |
| | 2 | 0.83 | 0.40 | 0.27 | 0.21 | 0.17 | 0.66 | 0.38 | 0.27 | 0.22 | 0.19 | 0.31 | 0.24 | 0.19 | 0.17 |
| | 5 | 0.92 | 0.42 | 0.28 | 0.22 | 0.18 | 0.65 | 0.36 | 0.27 | 0.20 | 0.16 | 0.20 | 0.15 | 0.13 | 0.11 |
| | 10 | 0.96 | 0.44 | 0.31 | 0.24 | 0.20 | 0.64 | 0.36 | 0.25 | 0.19 | 0.16 | 0.18 | 0.11 | 0.10 | 0.09 |
| T=1 s | 1 | 0.66 | 0.32 | 0.21 | 0.17 | 0.13 | 0.67 | 0.36 | 0.26 | 0.20 | 0.15 | 0.35 | 0.25 | 0.19 | 0.16 |
| | 2 | 0.80 | 0.32 | 0.21 | 0.16 | 0.13 | 0.60 | 0.34 | 0.24 | 0.19 | 0.15 | 0.26 | 0.20 | 0.16 | 0.14 |
| | 5 | 0.90 | 0.37 | 0.25 | 0.18 | 0.14 | 0.60 | 0.33 | 0.23 | 0.18 | 0.14 | 0.16 | 0.12 | 0.10 | 0.09 |
| | 10 | 0.95 | 0.42 | 0.29 | 0.21 | 0.18 | 0.59 | 0.32 | 0.23 | 0.18 | 0.14 | 0.14 | 0.09 | 0.08 | 0.06 |

Figure 2. 95th percentiles of the 6-minute time-average BS gain fraction of the theoretical maximum. Columns delimit the codebook beamforming (CB), MRT and ZF precoding strategies implemented with 4, 16, 36, 64 and 100 active antenna elements at the BS. Rows show scenarios with the UE connection duration of 1 s, 10 s and 60 s with 1, 2, 5, and 10 simultaneously active UEs. Cell color transparency is proportional to its value, ranging from fully transparent for zero to deep blue for one.



| Scheme | | CB | | | | | MRT | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| K \ N | | 4 | 16 | 36 | 64 | 100 | 4 | 16 | 36 | 64 | 100 |
| T=60 s | 1 | 0.70 | 0.40 | 0.31 | 0.23 | 0.22 | 0.73 | 0.43 | 0.32 | 0.25 | 0.22 |
| | 2 | 0.82 | 0.40 | 0.27 | 0.23 | 0.19 | 0.66 | 0.39 | 0.28 | 0.23 | 0.18 |
| | 5 | 0.92 | 0.43 | 0.29 | 0.23 | 0.19 | 0.64 | 0.36 | 0.27 | 0.20 | 0.16 |
| | 10 | 0.96 | 0.43 | 0.31 | 0.24 | 0.22 | 0.64 | 0.37 | 0.26 | 0.20 | 0.16 |
| T=10 s | 1 | 0.65 | 0.33 | 0.23 | 0.17 | 0.14 | 0.66 | 0.36 | 0.26 | 0.20 | 0.16 |
| | 2 | 0.80 | 0.34 | 0.22 | 0.17 | 0.14 | 0.62 | 0.34 | 0.24 | 0.19 | 0.15 |
| | 5 | 0.90 | 0.39 | 0.26 | 0.18 | 0.15 | 0.61 | 0.33 | 0.24 | 0.18 | 0.14 |
| | 10 | 0.95 | 0.42 | 0.29 | 0.22 | 0.17 | 0.61 | 0.32 | 0.24 | 0.18 | 0.14 |
| T=1 s | 1 | 0.64 | 0.30 | 0.20 | 0.15 | 0.12 | 0.67 | 0.34 | 0.25 | 0.19 | 0.15 |
| | 2 | 0.79 | 0.32 | 0.21 | 0.15 | 0.12 | 0.61 | 0.32 | 0.24 | 0.18 | 0.15 |
| | 5 | 0.90 | 0.37 | 0.25 | 0.17 | 0.14 | 0.60 | 0.31 | 0.23 | 0.18 | 0.14 |
| | 10 | 0.95 | 0.40 | 0.29 | 0.21 | 0.17 | 0.60 | 0.31 | 0.23 | 0.17 | 0.14 |

Figure 3. 95th percentiles of the 30-minute time-average BS gain fraction of the theoretical maximum.

**S01-6 [11:45]**
**STUDENT PAPER**

### Protocol for 5G Personal RF-EMF Exposure assessment

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***Presented by: Maarten Velghe***

A new activity-based protocol for 5G microenvironmental measurements and survey studies for the assessment of personal RF-EMF assessment is proposed. This protocol provides a necessary update to reliably assess exposure in 5G technologies, as it addresses the main challenges to personal exposure measurements introduced by 5G NR. A systematic method to evaluate a user's auto-induced exposure is introduced by using an activity-based approach.

#### Introduction

Various methods have been developed to assess exposure to radiofrequency electromagnetic fields (RF-EMFs). Röösli et al. [1] proposed a protocol for such studies. In this protocol two basic types of RF-EMF exposure dosimetry studies are identified: population surveys (using measurements) and microenvironmental measurements. In a population survey, participants selected from the general public are given a personal exposure meter (PEM) and by keeping a diary of their activities, summary statistics on population exposure are obtained. In microenvironmental studies, a trained researcher performs the measurements in a way that represents the typical behaviour in the environment of interest. However, the 5th generation of telecommunications technologies (5G) will change the RF-EMFs to which the public is exposed [2], mainly because 5G NR (new radio) base stations use Massive Multiple-Input Multiple-Output (MaMIMO) to focus on user devices [3]. Hence, a person's downlink (DL) exposure will depend on whether they act as user. Thus, auto-induced exposure will no longer be limited to the UL exposure. Moreover, it is expected that the auto-induced fraction of the DL exposure will be the dominant component [4].

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## Abstract Collection