Hybrid Ray-Tracing/Finite-Difference Time-Domain method for user EMF-exposure assessment of a massive MIMO technology

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Summary

The paper presents a novel method for numerical assessment of the massive MIMO exposure. Ray-tracing is used for a site-specific propagation modeling and the Finite-Difference Time-Domain method is applied to evaluate exposure of a realistic human phantom in terms of the Specific Absorption Rate. We discuss in detail the impact of the coupling between the user equipment and the phantom on the massive MIMO channel and propose a technique to incorporate it into the ray-tracing results for a more accurate exposure estimate. We show that the coupling with the head results in up to 19 dB variation of the incident electric field.

Introduction

Over the past few years, massive multiple-input multiple-output (MIMO) has drawn a lot of attention in the research community as a potential candidate for a 5G wireless networks technology. It utilizes a large number of antennas at the base station (BS) side to concentrate the electromagnetic (EM) energy in a small region of space around the intended receivers. The user equipment (UE) is a single-antenna device that facilitates the channel estimation at the BS by the uplink (UL) transmission of pilot sequences. The BS uses channel knowledge to *decode* the UL and *precode* the downlink (DL) signals using linear schemes. Theoretical analysis [4] and measurements with existing test-beds in real-life scenarios [2] showed that such schemes perform nearly optimal if the number of the BS antennas is much larger than the number of the simultaneously served UEs.

By spatial focusing of the EM-power, massive MIMO is also expected to dramatically increase the energy efficiency. However, this does not necessarily imply reduced EMF-exposure of a user: on the one hand, total transmitted BS power decreases, on the other hand, it is strongly focused in the user's proximity.

Some recent studies aimed at numerical estimation of exposure of humans to massive MIMO. In [6] the statistical properties of the incident field due to the DL massive MIMO operation were modelled based on analytical distributions of system parameters. In [1] a stochastic channel model was used. The exposure was assessed in terms of incident power densities.

It was assumed that the line-of-sight (LOS) yields a worst-case exposure. In such a scenario the massive MIMO BS creates beams in the directions of the UEs (*beamforming*). However, in reality an obstructed LOS or non-LOS (NLOS) conditions are more likely to occur, in which the channels' amplitude distribution closely resembles independent identically distributed Rayleigh, being favourable for the system performance. In these scenarios no direct beams are formed and massive MIMO relies on constructive interference of multipath components.

In this contribution we present a novel approach for massive MIMO exposure assessment, which is based on a combination of the Ray-Tracing (RT) and the Finite-Difference Time-Domain (FDTD) methods [5]. The RT captures direction and relative phase of the incident radiation and the FDTD tool allows the use realistic human phantoms for exposure evaluation in terms of the Specific Absorption Rate (SAR).

Materials and methods

The proposed numerical approach consists of who parts: RT and FDTD.

RT software is used to simulate propagation in a deterministic environment, given its geometrical model. 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. Reflections, transmissions, and diffractions are calculated for all output rays, which represent flat wavefronts incident at the position of the UE. The massive MIMO channel matrix element h_i^j is calculated by taking a sum over all rays complex amplitudes

$$h_i^j = C \sum_{k}^{m_{i,j}} (\boldsymbol{\psi}, \boldsymbol{e}_{i,k}^j) \,,$$

where i, j are UE and the BS antenna element indices respectively, $\boldsymbol{\psi}$ is the UE antenna polarization vector, k is the index of the ray, $m_{i,j}$ is the total number of ray-paths found in the channel between UE I and BS element j, and C is the normalization constant.

The ray-optics approximation assumes that all interactions occur in the far-field of an antenna and antennas are modelled as free-standing entities. A UE (such as a mobile phone) is usually coupled with its user in the near-field, i.e. a mobile phone close to the user's head in a voice-call mode.

Firstly, this results in the modified radiation pattern of the UE antenna: signals in a certain range of direction-of-arrival (DOA) get attenuated and absorbed by the user body instead of being received by the UE.

Secondly, the presence of the user body introduces a phase shift into the received signal, which also depends on their DOA. Rays that are attenuated by the body are typically delayed, compared to the free-space propagation due to a lower speed of electromagnetic waves in absorbing tissues and lensing effects, which effectively increases the length of propagation paths.

These effects are accounted for using a set of FDTD simulations with a realistic human phantom. The DOA space is discretized in a nearly-uniform manner based on the face normal vectors of an icosahedral sphere (ico-sphere), which is generated by an incrementally subdividing the faces of the regular icosahedron until the desired angular resolution is achieved. A single-plane-wave simulation is performed for each face of the ico-sphere, in which the plane-wave has a fixed amplitude and its wave-vector is collinear with the normal vector of that face $\boldsymbol{n_i} \equiv (\theta_i, \varphi_i, 1)$ in spherical coordinate system. After the simulation reaches a steady-state, *phasor* of the E-field $\boldsymbol{A_r}(\theta_i, \varphi_i)$ is sampled at the point $\boldsymbol{r}$, where the UE is assumed to be located.

The amplitude of $\boldsymbol{A_r}$ is proportional to the open-circuit voltage gain due to the coupling with the phantom's body, relative to the isotropic radiator in free space. The argument of $\boldsymbol{A_r}$ is the phase shift of the incident radiation due to its interaction with the body.

The modified massive MIMO channel matrix, is then obtained by taking the sum over all rays, with their amplitudes multiplied by $\boldsymbol{A_r}$, evaluated with the DOA of each ray:

$$\widehat{h_i^j} = C \sum_k^{m_{i,j}} (\boldsymbol{\psi}, \boldsymbol{A_r}(\theta, \varphi))(\boldsymbol{\psi}, \boldsymbol{e}_{i,k}^j(\theta, \varphi)).$$

After the modified channel matrix $\widehat{h_i^j}$ is obtained, which should be close to the channel matrix measured in reality, the assessment of exposure could be performed with the method described in detail in [5].

Results

We calculated $\boldsymbol{A_r}$ for ViP 3.1 heterogeneous Duke phantom [3] using the Sim4Life v.4.0 (ZMT, Zürich, Switzerland) FDTD software package. A mobile phone in a voice call mode represented the UE and the E-field was sampled at $\boldsymbol{r}$ $(x = 0, y = 100mm, z = 0)$ with the phantom's head centered at the origin and its face aligned in the positive direction of the x-axis $(\theta = \frac{\pi}{2}, \varphi = 0)$ as shown at Figure 1. Simulations were conducted at 3.5 GHz frequency, the amplitudes of all plane waves were set to 1 V/m and ico-sphere with 320 faces was used to set their incidence directions. For simplicity, a vertically polarized UE antenna was assumed, such that $(\boldsymbol{\psi}, \boldsymbol{A_r}) = E_z$.

Figure 2 (Top) shows the voltage gain as a function of DOA. As expected, maximum gain is observed for the direct incidence $(\varphi = 3\pi/2)$; wave reflection from the head results in a 20% increase in the E-field (~1.2 V/m, see Figure 1). The lowest gain is observed when the head is obstructing the direct line of incidence $(\pi/4 < \varphi < 3\pi/4)$. On average it results in around -10 dB attenuation with the minimum of -18 dB. The attenuation in elevation is mostly due to the antenna polarization effect and proportional to $\sin(\theta)$.

Figure 3 (Bottom) depicts the phase of E_z as a function of DOA. The function is largely flat for angles of direct incidence and varies significantly for obstructed paths. A discontinuity can be seen near $\pi/2 < \varphi < 3\pi/4$, which suggests that a finer incidence discretization is required.

Conclusion

A novel numerical approach for massive MIMO human exposure assessment was presented. Simulations show that the user body strongly affects the amplitude (1 to -18 dB variation) and the phase of the signal sensed by a closely located receiver. A method to incorporate this effect into the massive MIMO channel and exposure estimation with a ray-tracing tool [5] was proposed.

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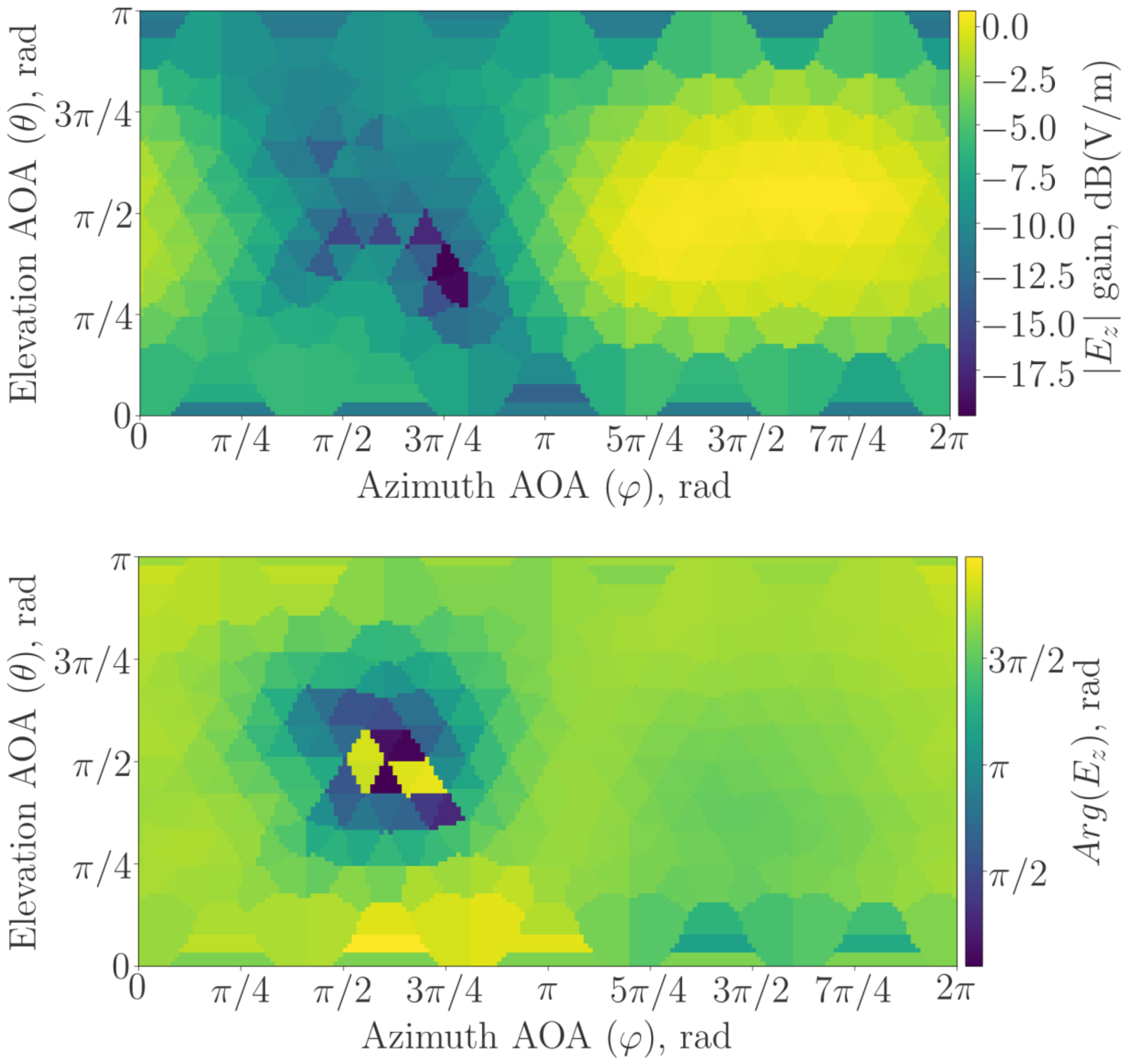

Figure 2. Top: Gain of the vertical polarization component of the E-field for the UE positioned next to the left side of the phantom's head. Bottom: Phase of the vertically polarized E-field as a function of direction of incidence. φ = 3π/2 rad (azimuth) and θ = π/2 rad (elevation) correspond to the direct incidence to the UE, and φ = π/2 correspond to the signal blocked by the head.

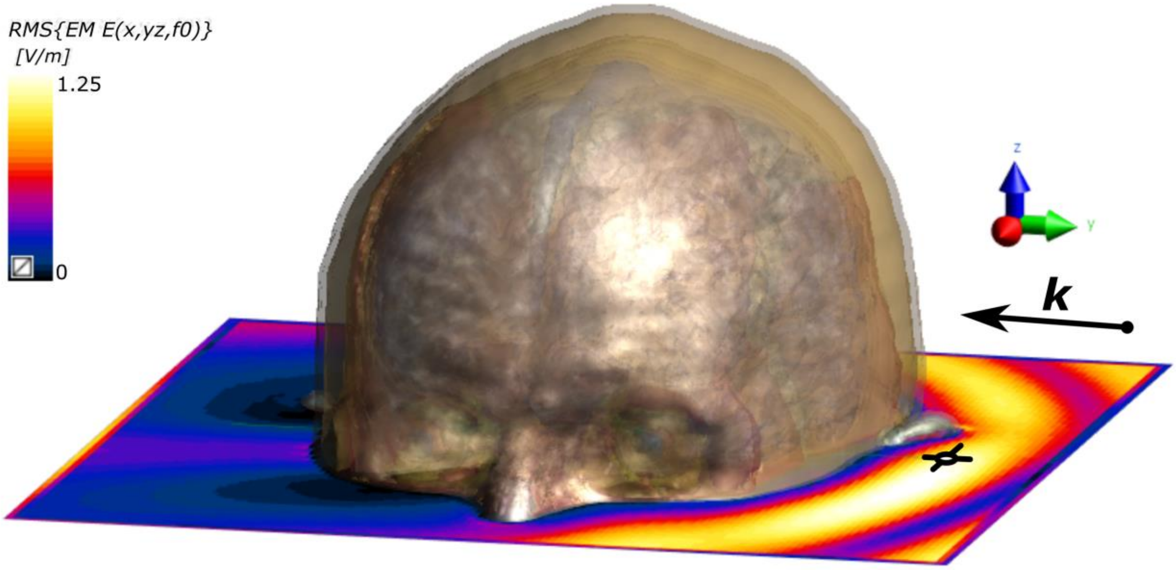

Figure 1. E-field distribution inside the FDTD domain in a horizontal slice at z=0. Point **r** is depicted with a black cross to the left of the phantom's head. The wave-vector **k** of the incident plane wave is shown with a black arrow.