New Hybrid QuaDRiGa-FDTD Method for Realistic Human Exposure Assessment at 28 GHz with 6G Cell-Free Massive MIMO in 3D Outdoor Environments

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BioEM 2023, Oxford, England, June 18-23, 2023

SUMMARY

A new computational method for realistic exposure assessment is presented for millimeter-wave 5G and 6G networks. For 5G, collocated Multiple-Input-Multiple-Output (MIMO) base stations beamform the signal toward the user and create hotspots of increased exposure. For 6G, cell-free Massive MIMO (MaMIMO) networks use a large number of access points (APs) distributed over the urban landscape. The propagation of the fields through the environment is hybridized with the computation of the exposure on a virtual human. A trajectory from Google Maps between any two addresses in the world is placed in a 3D mesh from Google Earth, semantically labeled with a machine-learning model. In the propagation step, APs are distributed on the faces of buildings using Poisson Disk sampling. This data is used by QuaDRiGa, a powerful quasi-deterministic channel generator, to obtain channel realizations as a function of time. After precoding the signal, the total fields are evaluated on a Huygens surface around the head of a detailed virtual phantom. These form the input to the exposure step, where an FDTD simulation is performed. A post-processing step yields the surface absorbed power density at 28 GHz. The method is applied to a walk through central Helsinki. The range of exposure from a 5G collocated base station is 100 times (20 dB) higher than that of a cell-free MaMIMO network. A precoding gain of up to 20 dB is observed only for the beamforming collocated base station.

INTRODUCTION

The fifth generation of cellular networks (5G) addresses the ever-increasing demands in internet connectivity. Infrastructure for the sub-6 GHz bands is becoming widespread, with some cellular providers even deploying millimeter-wave base stations. For the latter, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) updated its guidelines in 2020 with the new surface absorbed power density metric [1]. Research into the most realistic modeling of human exposure possible is important not only from a public health perspective, but also to plan the locations and powers of base stations in future 5G and 6G cellular networks. For 5G, complex new technologies were introduced, such as Massive Multiple-Input-Multiple-Output (MaMIMO). The signal can be beamformed towards the user and hotspots appear at the User Equipment (UE) [2]. For 6G, *cell-free* MaMIMO is proposed as prospective new technology, where a very large number of synchronized Access Points (APs) are distributed throughout a large geographical area. To model the exposure from these technologies, the propagation step needs to be interfaced with the exposure step in one integrated method [3].

While a multitude of methods provide channel realizations in a network, none yield a realistic assessment of the exposure. One of the widely used channel generators is a ray tracer (RT), which can be integrated with the exposure step [3]. Rays shoot out from the transceivers (Tx), propagate and scatter through the environment and are collected at the receivers (Rx). However, hybrid RT/FDTD is computationally challenging because the full electromagnetic fields for many Directions of Arrival (DoAs) need to be loaded to memory [2]. Moreover, data on the dielectric parameters and scattering of the materials is fairly limited, especially at mm-wave frequencies. In this paper, we use the state-of-the-art QUAsi Deterministic RadIo channel GenerAtor (QuaDRiGa) [4]. A number of scattering clusters are stochastically generated around the receiver based on spatially-correlated parameter maps of the environment. With the positions of the clusters known, a deterministic channel is obtained along the path of a moving user. This open-source model and its previous iterations have been validated for over two decades and comply with the 3GPP guidelines [4]. For the hybridization step we use a Huygens surface, requiring saving the fields only on the surface of the box [5].

QuaDRiGa is an ideal channel generator to hybridize with the exposure step for three reasons. First, it provides realistic channels because the statistical parameters generating the parameter maps are derived from measurement campaigns [4]. In addition, version 2.0 features full spatial consistency in the channels, which is important when modeling the resulting exposure along a path [4]. Finally, the method is ideal for cell-free MaMIMO to quickly generate the numerous required channels in a spatially-correlated way.

This paper presents a new hybrid QuaDRiGa-FDTD method. To the best knowledge of the author, it represents the following novel contributions. First, the use of 3D outdoor Google Maps data to compute the realistic exposure along any path. Second, a hybrid propagation-exposure method to compute the exposure of a cell-free MaMIMO network at millimeter-waves. Third, a hybrid propagation-exposure method computes the exposure as a function of location and time. Finally, a comparison between collocated and cell-free MaMIMO in both user and non-user scenarios.

METHODS

Configuration

Figure 1 shows the configuration studied in the results. Here, hybrid QuaDRiGa-FDTD is applied to a single-user scenario of a 6G cell-free massive MIMO network and compared with a 5G collocated MIMO antenna. Signals are precoded towards a smartphone held in the hand of a pedestrian, walking in Helsinki between 60° 9' 40.0248" N, 24° 56' 41.0496" E and 60° 9' 46.2168" N, 24° 56' 36.0276" E. The total distance of the walk is 273 m. The pedestrian is in an urban environment in the first and last 50 m. In between, the user walks through the park of St. John's church in central Helsinki. Due to the increased vegetation and absence of buildings, the environment in this section is suburban. A collocated 8x8 MIMO antenna is placed on the tower of the church, facing south and tilted down by 15°.

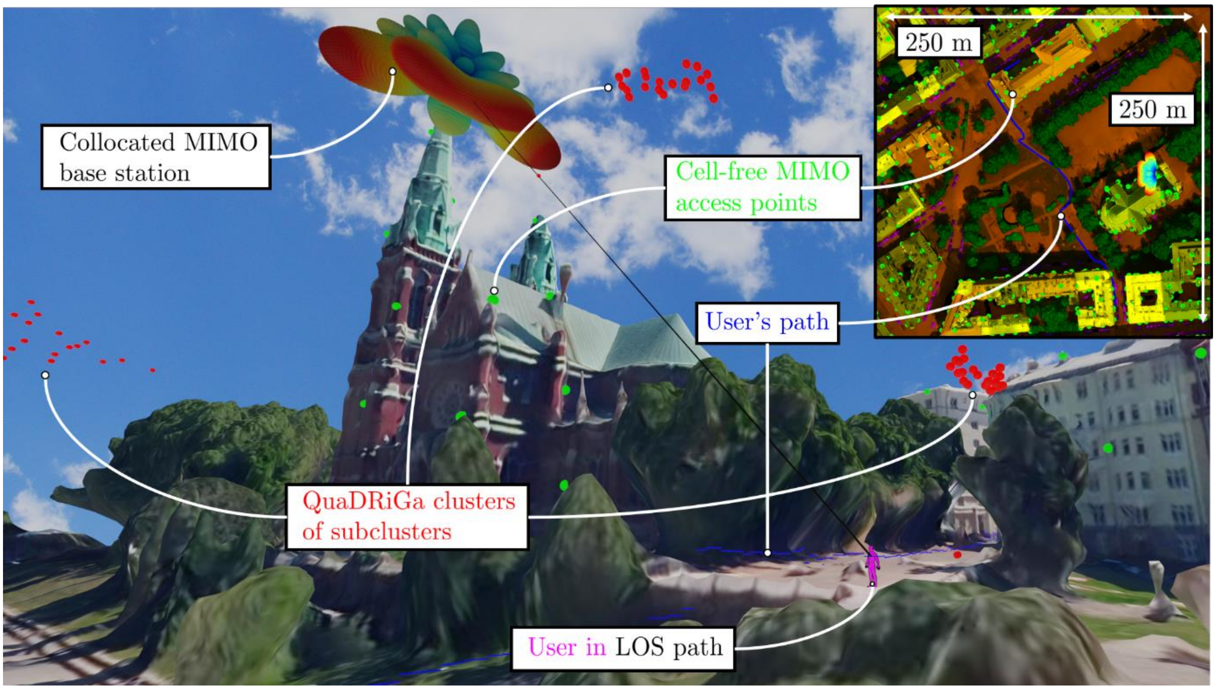

Figure 1: Configuration of the example discussed in the results. A cell-free MIMO network (green) is simulated. Alternatively, a collocated MIMO base station beamforms towards the user (purple) at a snapshot with a LOS path (black). At this snapshot, the QuaDRiGa clusters, composed of subclusters (red), are shown. The inset depicts the user's path (blue) walking from bottom to top.

In general, a configuration is defined only by the addresses of the origin and destination of all users. Using the Google Maps API, a path is returned describing the walking route of the user. Points on the path follow the curvature of the sidewalks. Their resolution is in the order of several meters. The user walks at a constant speed of 1.4 m/sec. The straight walk is sampled in snapshots at a frequency based on the sampling theorem of the Doppler spectrum [4]. To eliminate discontinuous changes in direction of travel, the user is modeled to always walk towards the point that is 2 m ahead on the straight path.

A 3D mesh of the environment around the path is retrieved from Google Earth [6]. Google Earth provides one of the most extensive datasets for 3D imagery, allowing the user to pick any two addresses in the world as inputs. The Semantic Urban Mesh (SUM) machine learning model [7] is a performant state-of-the-art machine learning model that classifies textured mesh faces as either terrain, building, high vegetation, water, vehicle or boat. The model was trained on 4 km^2 of central Helsinki, using a textured mesh with a ground sampling distance of 7.5 cm. The Google Earth meshes have a similar resolution and can be semantically classified by the open-source pre-trained SUM model.

Propagation step

A 6G Access Point Network (APN) is envisioned to have hundreds of antennas distributed on the facades of buildings. First, building mesh faces whose normal have an azimuthal angle between 70 and 90 degrees and with heights 3 meters above the ground, are selected. Then, uniform Poisson disc sampling with a minimum distance of 10 m is performed using the efficient Bridson's algorithm. Finally, only locations within 175 m of the user's path are considered. At these locations, vertically-polarized patch antennas model APs. 1.25 m above the nearest ground mesh, vertically-polarized omnidirectional antennas model the UE (e.g. a smartphone) being held by the pedestrian. For each point in the path, we assign a channel scenario based on the type of environment, e.g., dense urban, suburban or rural. For each access point, if the Line-Of-Sight (LOS) connection is obstructed by any face, it is classified as Non-Line-Of-Sight (NLOS).

The QuaDRiGa tool is used to generate realistic quasi-deterministic impulse responses from each access point to each receiver across time. Within each channel scenario, a spatially-consistent map of the large-scale parameters (LSPs) is generated. These are based on available configuration files containing their stochastic information extracted from measurement campaigns in urban and suburban Berlin and in LOS and NLOS [4]. A number of Last-Bounce-Scatterer (LBS) clusters with each 20 subclusters are generated around the user. The birth and death of clusters together with interpolations of their positions and powers also assure spatial consistency in the transitions between channel scenarios. Therefore, the hotspot shape and exposure metrics consistently conform to the path and environment variations. Computing the exposure from each subcluster and from each access point is too computationally expensive. Instead, at most 180 ($N_{subclusters}$) beams with the greatest power are selected for a combined channel. Unselected subclusters have their total power spread uniformly over the selected ones. Multi-user scenarios can be implemented by defining an origin and destination address for each receiver and repeating the above steps. QuaDRiGa is adapted to yield a 4-D channel tensor of dimensions N_{rx} x N_{tx} x $N_{subclusters}$ x $N_{snapshot}$, which is precoded using Maximum Ratio Transmission (MRT), and the positions of the subclusters at each snapshot. With MRT, exposure from an unprecoded channel is equivalent to a non-user MIMO scenario.

Hybridization step

The channel coefficient $c_{r,t,l,s}$ for a vertically-polarized omnidirectional receiving antenna are given by

$$c_{r,t,l,s} = \mathbf{E}_{r,t,l,s} \cdot \mathbf{e}_{\theta}\left(\theta_{r,l,s}, \phi_{r,l,s}\right) . \tag{1}$$

We now compute the total fields on the bounding box around the user's head. Their coordinates $\mathbf{r}(x, y, z)$ are with respect to the origin $\mathbf{r}_{\text{head}} = \mathbf{T} + \mathbf{r}_r$, where $\mathbf{T}$ is the translation between the user's smartphone and head. The expression for a spherically expanding plane wave (SPW) from a subcluster to $\mathbf{r}(x, y, z)$ is

$$\mathrm{SPW}(x,y,z)=\frac{\exp\left(i\ 2\pi f/c\ \left|\mathbf{r}(x,y,z)+\mathbf{T}+\mathbf{v}_{r,l,s}\right|\right)}{\left|\mathbf{r}(x,y,z)+\mathbf{T}+\mathbf{v}_{r,l,s}\right|}\ ,$$

where $\mathbf{v}_{r,l,s} = \mathbf{r}_{r,s} - \mathbf{r}_{l,s}$. We normalize SPW with respect to amplitude and phase at $\mathbf{v}_{r,l,s}$ and replace the amplitude and phase with the channel coefficient:

$$\mathbf{E}_{r,t,l,s}(x,y,z) = c_{r,t,l,s}\ \mathrm{SPW}(x,y,z)\ \exp\left(-i\ 2\pi f/c\ \mathbf{v}_{r,l,s}\right)\left|\mathbf{v}_{r,l,s}\right|\mathbf{e}_{\theta}\left(\theta_{r,l,s},\phi_{r,l,s}\right).$$

By summing over all Tx and subclusters, we obtain

$$\mathbf{E}_{r,s} = \sum_{t,l}\mathbf{E}_{r,t,l,s}\ ,$$

$$\mathbf{H}_{r,s} = \sum_{t,l}\frac{1}{Z_0}\hat{\mathbf{v}}_{r,l,s}\times\mathbf{E}_{r,t,l,s}\ .$$

These total fields inside the bounding box are a solution of Maxwell's equations. Therefore, the fields inside the bounding box are completely determined by the fields on the surface of the box. Using a Huygen surface, the equivalent surface currents can be defined as

$$\mathbf{j}_{\mathrm{surface}} = \hat{\mathbf{n}}\times\mathbf{H}_{\mathrm{surface}}\ ,$$
$$\mathbf{m}_{\mathrm{surface}} = \mathbf{E}_{\mathrm{surface}}\times\hat{\mathbf{n}}\ . \tag{2}$$

Note that this also causes the memory requirements to scale quadratically with frequency instead of cubically. The surface is gridded with a resolution of at least 10 cells per wavelength. The resulting fields model the real field distribution with local spherical plane waves, instead of the sum of local plane waves from a discrete set of DoAs as in [3].

Exposure step
MRT precoding beamforms the fields toward $\mathbf{r}_{r,s}$, causing a significant gain in particular for collocated antennas [2]. The alignment of phases from different beams causes an additional hotspot gain at $\mathbf{r}_{r,s}$ if $\mathbf{T} = 0$. As reference quantities are determined in free-space receiving scenarios, the time-averaged incoming power density $|\mathrm{Re}(S_{\mathrm{inc}})|$ is readily available. To account for the latter effect outside of free-space receiving scenarios, the coupling with the head needs to be included in (1) by incorporating a DoA-dependent antenna factor [3]. For each DoA, the full-wave simulations should include the human body and a realistic receiver antenna. For the configuration studied here, we choose $\mathbf{T} = -50\ \mathrm{cm}\ \mathbf{e}_x + 50\ \mathrm{cm}\ \mathbf{e}_z$, with the x-axis in the direction of travel. Thus, including head-coupling is not necessary as no hotspot gain is present.

The currents in (2) form generalized total-field scattered-field (TFSF) sources in an FDTD simulation that includes the Multimodal Imaging-Based Detailed Anatomical Model of the Human Head and Neck (MIDA) [8] as virtual phantom, featuring a spatial isotropic resolution of 500 µm. The head is oriented along the user's path. In FDTD simulations, the number of unknowns scale as f^3 and the simulation time as f [2]. However, all impulse responses for each DoA do not need to be kept in memory as in [3]. Millimeter-wave 5G and 6G operate at frequencies above 6 GHz, e.g. 28 GHz. The maximum time-averaged surface absorbed power density S_{ab} (in $\mathrm{W/m^2}$) over a 4-$\mathrm{cm^2}$ surface is used to better account for the superficial nature of the exposure [1]. This exposure quantity is computed in a post-processing step with the skin of the virtual phantom.

RESULTS
The method is applied to the central Helsinki configuration with a carrier frequency of 28 GHz. Therefore, the sampling rate is 53 Hz and the total number of snapshots is 9905. 335 distributed APs were generated in the $250\ \mathrm{m}\times 250\ \mathrm{m}$ mesh considered around the path. The FDTD grid and Huygens

surface have a resolution of 15 cells per wavelength resulting in a grid of $302 \times 230 \times 323$ cells. The average computation time for one snapshot of hybrid QuaDRiGa-FDTD is $160\ sec$.

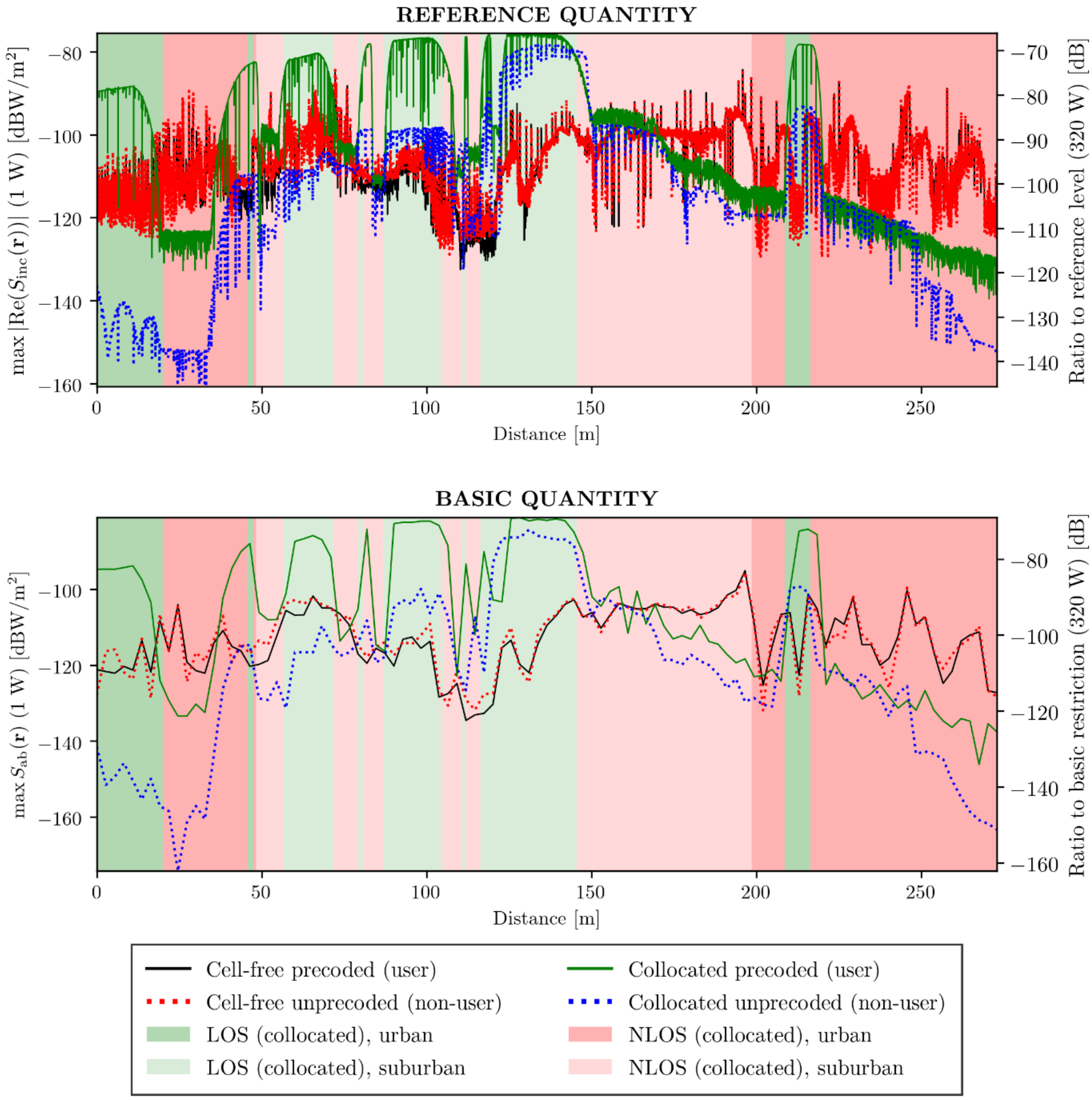

Figure 2: Reference and basic quantities as a function of distance along the path. The exposure is compared for precoded and unprecoded channel matrices, and compared for cell-free and collocated MaMIMO. Colored patches indicate the type of propagation environment along the path of the user. The left axis expresses the exposure for normalized powers per antenna element. The right axis expresses the exposure as a ratio for a typical total power of 320 W.

Figure 2 shows the reference and basic quantities as a function of distance along the path. The exposure is compared for precoded (user scenario) and unprecoded (non-user scenario) channel matrices, and compared for cell-free and collocated MaMIMO. Colored patches indicate the type of propagation environment along the path of the user. The left axis expresses the exposure for normalized powers per antenna element. The right axis expresses the exposure for a typical total power of 320 W. This is done by dividing the metrics by their maximum permissible levels. For the general public in this case, the reference level is 10 $\mathrm{W/m^2}$ and the basic restriction is 20 $\mathrm{W/m^2}$. The maximum of these ratios is 0.05% for a collocated base station precoding the channel in a LOS suburban propagation environment. The range between the minimal and maximal S_{ab} exposure is about 20 dB or 100 times greater with a precoded channel compared to an unprecoded channel, because the beams are steered in the direction of the user. This effect almost completely vanishes for cell-free MaMIMO. At any time, only a few APs from different locations serve the user. The precoding gain is completely determined by the alignment of their phases, making beamforming impossible. The range for the cell-free MaMIMO network is also 20 dB smaller than for collocated MIMO. This is because the path loss is highest at the start and finish of the path. In these urban regions, the user is also in NLOS due to the obstruction of the buildings. The cell-free APN causes a more uniform exposure along the path because, most of the time, at least one AP is in LOS with the user. From a network-planning standpoint, more power can be fed to a 6G cell-free MaMIMO system compared to a 5G collocated one, while avoiding regions of excessive exposure. Furthermore, we observe the continuity of the channel across time for large-scale fading and report continuity for small-scale fading. Finally, a high correlation is observed between the channel coefficients, reference quantities and basic quantities, as was also found in [2].

CONCLUSIONS

Realistic exposure assessment is important from a public health and network-planning perspective. A new hybrid QuaDRiGa-FDTD method based on 3D outdoor environments addresses this need in 5G and 6G networks. A walk through central Helsinki was simulated for a cell-free and collocated MaMIMO system and compared for user and non-user scenarios. The cell-free MaMIMO system shows more uniform exposure. Only collocated MIMO caused a beamforming gain. Future work will first focus on the impact of the hotspot gain, e.g., when holding the phone near the head. The computational requirements of hybrid QuaDRiGa-FDTD scale well into sub-THz 6G frequencies. It also enables virtual field trials for advanced network planners that take into account the exposure constraints.

ACKNOWLEDGEMENTS

This work was supported by Methusalem through “SHAPE: Next Generation Wireless Networks”.

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