WHITE PAPER

How to Design Base Station (or Microcell) Antenna Arrays for 5G Wireless Networks

This paper describes a simulation workflow in Ansys HFSS to design 5G base station (or microcell) arrays. It looks at tackling problems related to the antenna's beamforming capabilities that use multiple-input-multiple-output (MIMO) techniques. In addition, it describes the modeling techniques for massive millimeter-wave (mm-wave) antenna arrays before their deployment on a microcell or base station. Final stages of the workflow involve analyzing practical scenarios comprising an end user equipment UE and the microcell. To characterize the communication channel between the UE and microcell, channel state information (CSI) is extracted and subsequently used in designing MIMO beamforming approaches. Real-world indoor and outdoor 5G wireless communications scenarios and applications are used to illustrate the efficacy of this workflow. Engineers interested in creating end user devices or UEs such as smartphones, smartwatches and similar hi-tech smart devices will benefit from the uniform simulation workflow described in a separate paper, "How to Design UE Antenna Systems for 5G Wireless Networks."

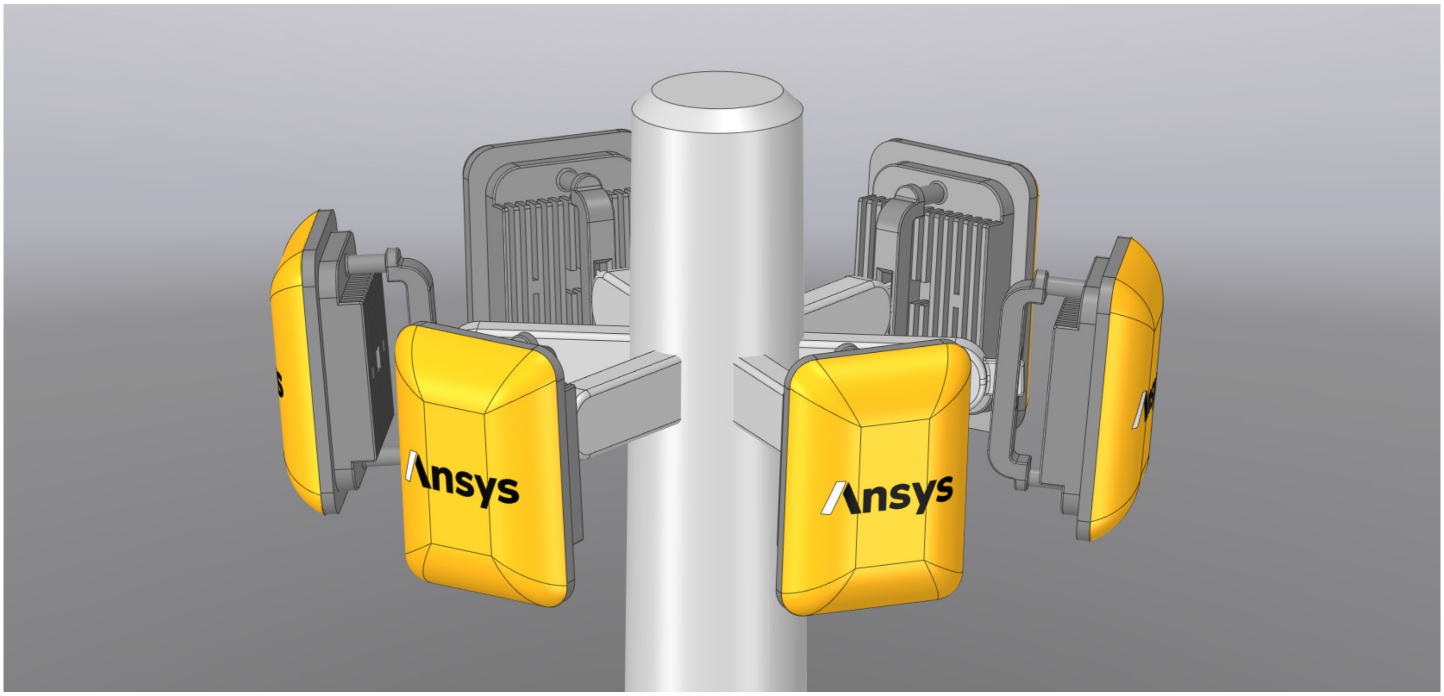

Figure 1. A virtual model in Ansys HFSS of 5G antenna arrays mounted on a mast

/ Microcell Array

Since the millimeter-wave frequency has shorter wavelength than current 4G frequency bands, you can fit a greater number of antenna elements in a 5G microcell array within the same space. In other words, in 5G microcells, because the frequency range is extended to the mm-wave regime, more elements can be integrated into the same physical aperture compared with previously designed sub-6 GHz arrays. The mutual coupling, loss and radome effects are less known in mm-wave and, therefore, a full-wave simulation and modeling platform is necessary for designing the microcell arrays. Ansys HFSS offers a streamlined workflow for designing arrays. It begins with the selection of the proper element and uses a “unit cell” to study a single antenna’s performance as an element of an array extended into infinity in lateral directions. Infinite array approximation does not capture the edge effects but provides valuable information about the element’s polarization and the array’s potential blind angle if the beam is scanned. This computationally low-cost technique is the initial step in the design. From the single antenna element, an explicit truncated array is created. Ansys HFSS offers the finite array domain decomposition method (FADDM) as a full-wave solver to tackle large-scale array problems by making optimum use of memory and CPU. FADDM is a full-wave solution that incorporates the edge effects and calculates mutual coupling. Using FADDM, engineers can optimize the array elements and the excitation values to achieve the desired outcome in terms of bandwidth, beam width and gain.

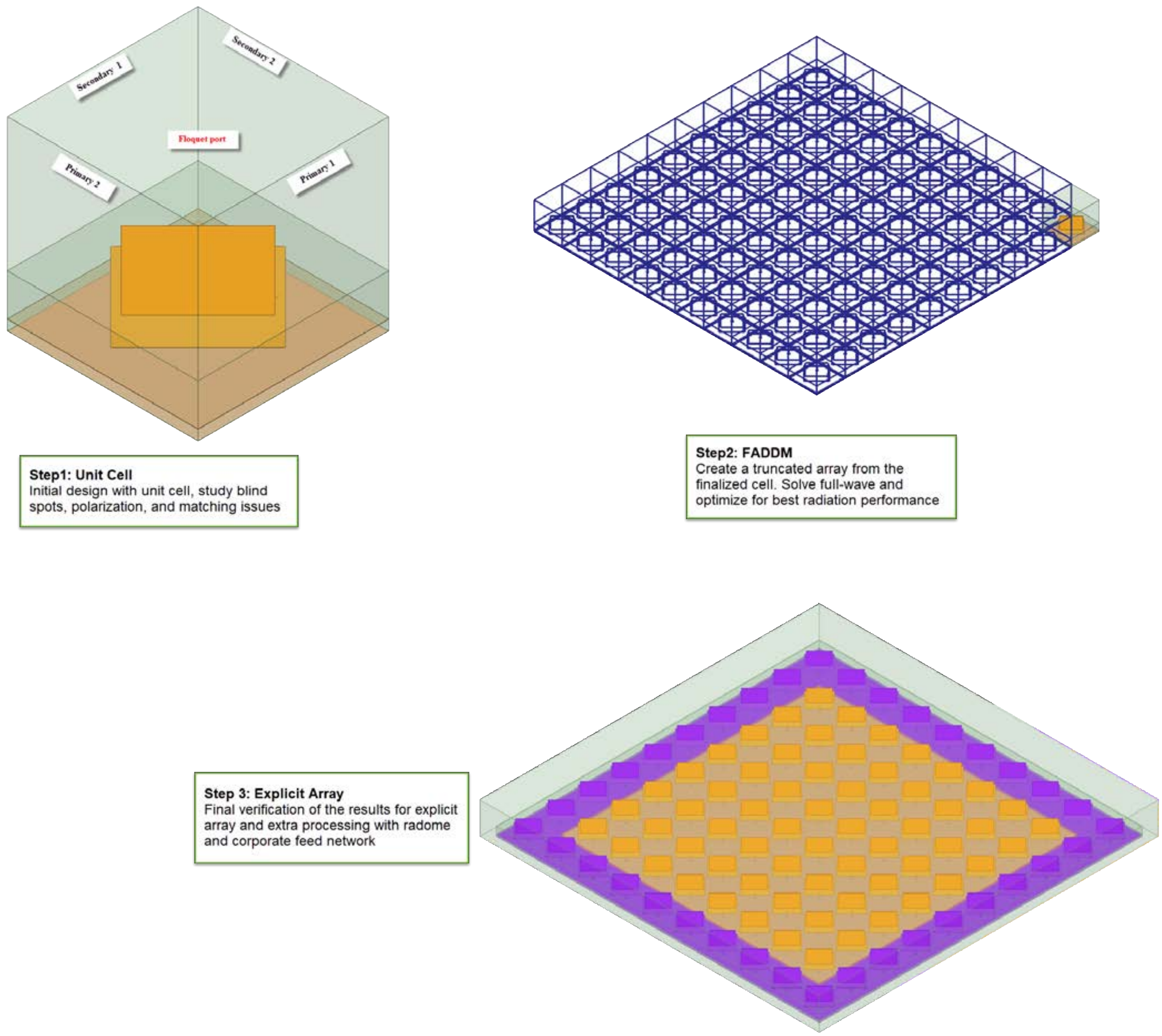

Figure 2. A workflow to design antenna arrays in Ansys HFSS

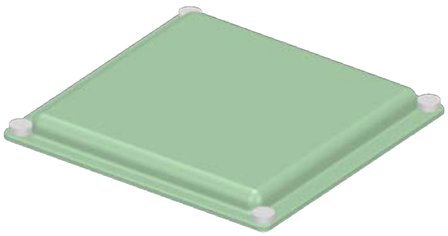

Figure 3. Array with radome

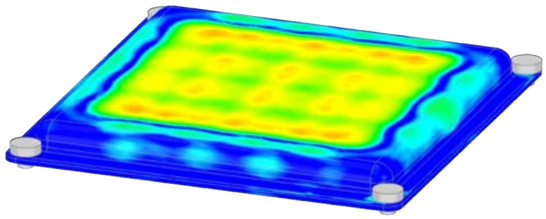

Figure 4. Electric field of the array radome assembly

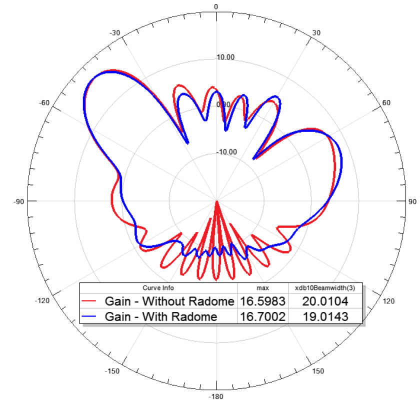

Figure 5. Gain plot

/ Beamforming Using Massive MIMO

A virtual city model can be used in HFSS to represent a practical scenario (Figure 6) where the microcell is deployed in an urban area comprising buildings, vehicles and pedestrians carrying user equipment. The communication channel between the microcell and a single UE (smartphone) is complex, consisting of many obstacles. In 5G, with mm-waves bouncing from buildings, roads, pedestrians, cars and other objects, the multipath propagation issues are intensified. They undergo absorption and multi-path reflections from these obstacles and arrive at the receiver with decaying amplitudes and different time delays. Modeling complexities increase when dynamic scenarios are considered. For instance, a dynamic scenario could include pedestrians walking with their user equipment and vehicles moving on the road.

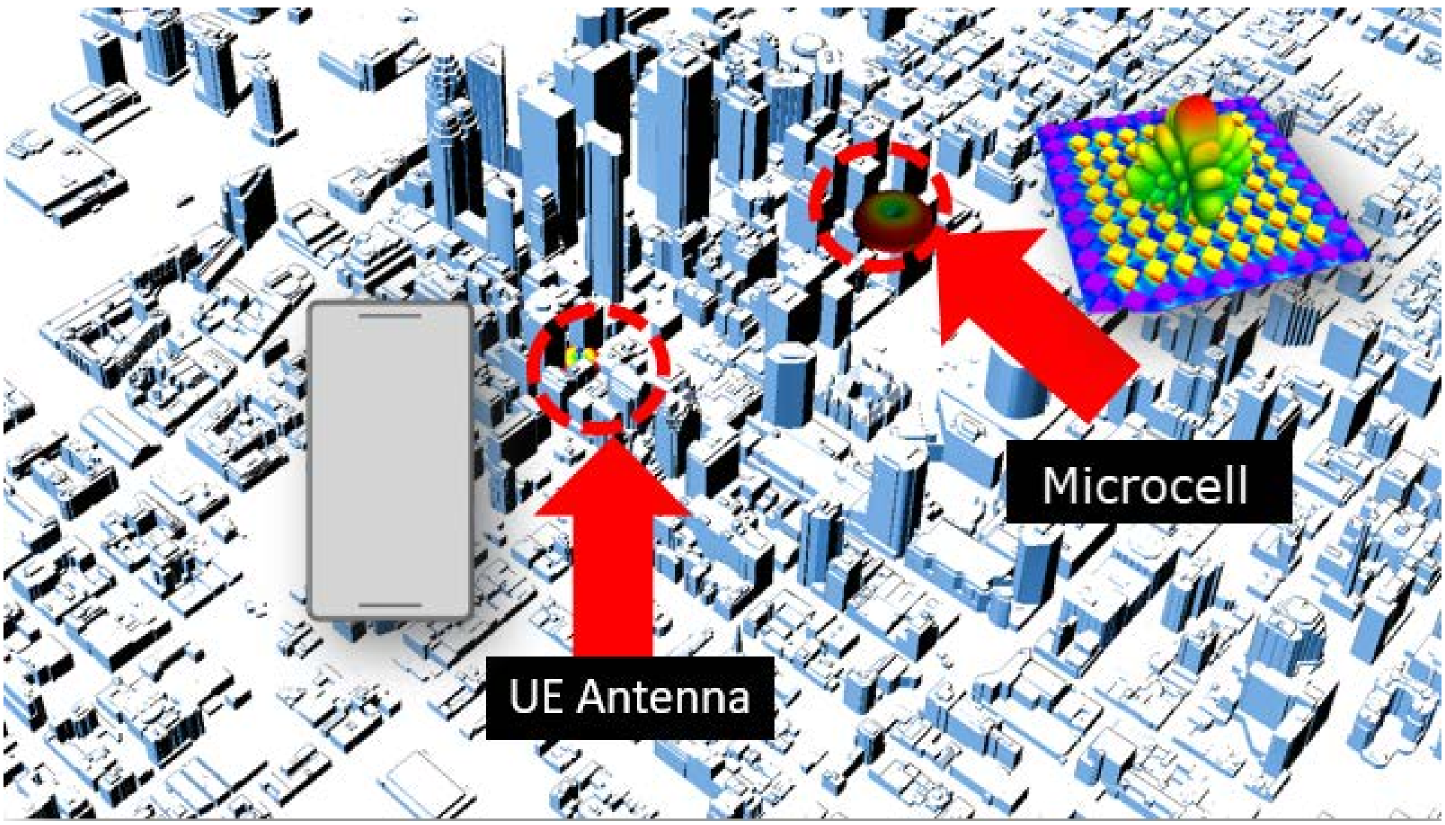

Figure 6. UE and microcell communicating in a city

Figure 4 demonstrates the radome effect on the radiation gain pattern at 28 GHz. The 5G microcell should be able to service multiple users at a time on the same dedicated frequency band to efficiently utilize the frequency bandwidth and improve the channel capacity. To achieve these objectives, traditional beamforming techniques that rely on phased arrays to direct the beam to a single receiver are not efficient. On the other hand, MIMO arrays are well-suited for communicating with multiple user equipment devices simultaneously.

In previous generations (e.g., 4G), the operating frequencies were restricted to the sub-6 GHz band, thereby limiting the number of elements that could be fitted on a finite-sized array. By switching to mm-waves, the smaller wavelengths allow the same physical aperture in the array to accommodate more antenna elements, resulting in massive MIMO systems. The higher number of elements increases the array's flexibility to form a greater number of beams and steer them in the intended directions. Advanced simulation tools such as HFSS can help design an array using an appropriate number of antenna elements to provide optimal beamforming, offering the best trade-offs between the array size and cost.

Modeling the communication channel between the UE and microcell array is challenging and requires the extraction of the channel state information (CSI), which is described in the next section.

/ Extracting Channel State Information

Massive MIMO antenna systems are well-suited to operate in the time division multiplexing modes (TDD) by exploiting channel reciprocity. To acquire the channel state information in the time domain multiplexing mode, a pilot signal is transmitted on the uplink from the user equipment. The signal goes through the communication channel and arrives at the microcell array elements. This pilot signal is used to prepare the microcell for serving multiple users simultaneously. The received signal (a complex value, mag/phase) carries valuable information about the channel used by the MIMO algorithm for beamforming. The scattering matrix **[S]** is a good representation of the channel state information and is used to extract channel response or the **[H]** matrix. The **[H]** matrix is a subset of the **[S]** matrix where the diagonal terms of **[S]** (i.e., reflection coefficients) are eliminated. Only mutual coupling terms between the microcell and UEs are preserved while other terms are neglected. These mutual coupling terms represent how a signal is transmitted between elements of the microcell array and multiple user equipment devices. In other words, within the [H] matrix the element **hij** represents the connection between the *i*th element of the microcell array and the *j*th user equipment through the communication channel.

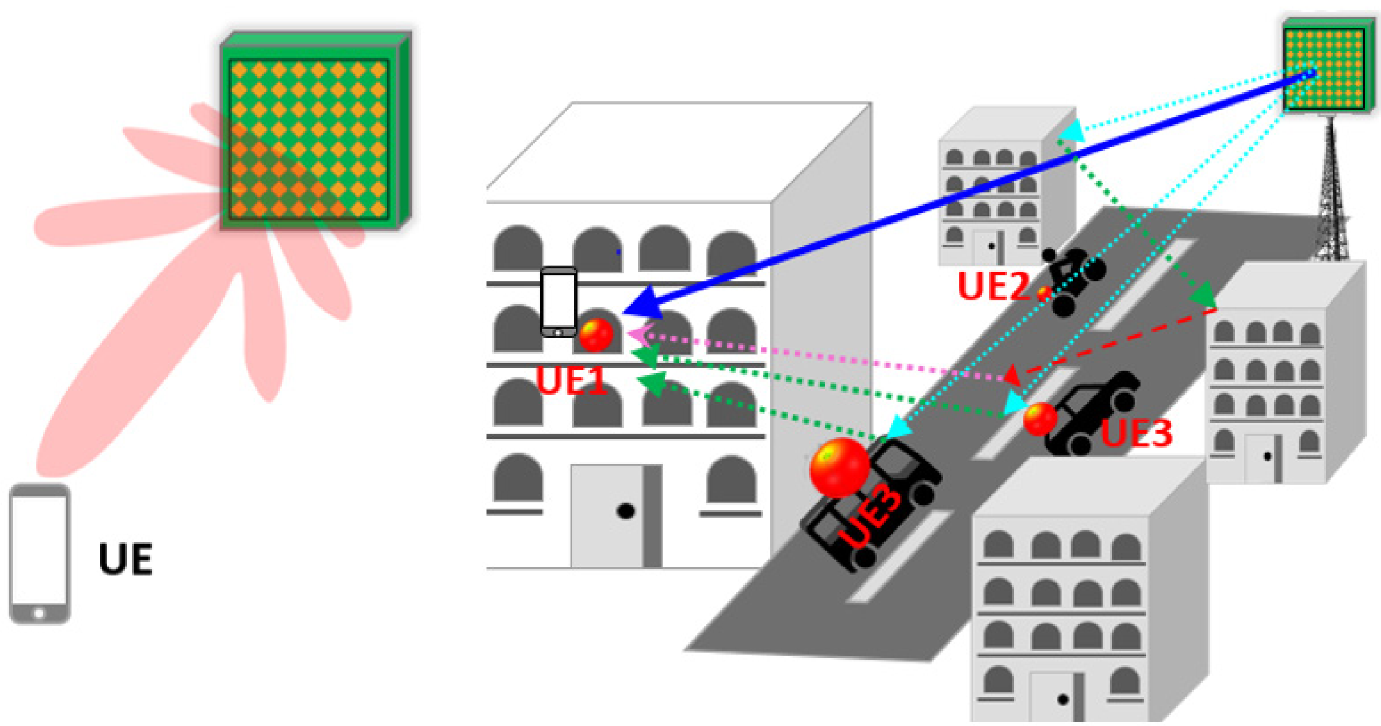

Figure 7. Potential for multiple and multipath reflections makes the communication channel complex and consequently beamforming is challenging.

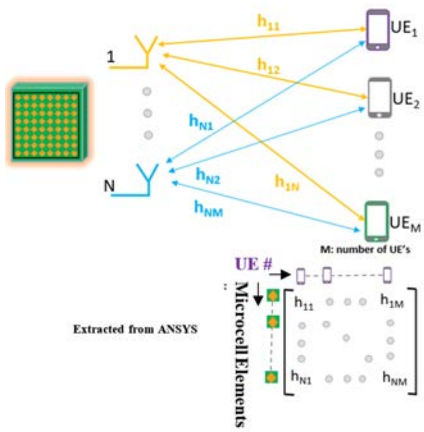

Figure 8. Extracting channel state information matrix [H] from HFSS simulation results in term of a subset of [S] matrix.

Common MIMO Algorithms	
Technique	**Function**
Maximum Ratio (**MR**)	$W^{MR} = H^h$
Zero Forcing (**ZF**)	$W^{ZF} = (H^*H)^{-1} H^h$
NMSE or **RZF**	$W^{RZF} = (H^hH+\beta I)^{-1} H^h$

Table 1. Common MIMO algorithms

/ Examples

In this section, two examples demonstrating the proposed workflow for modeling multi-user massive MIMO at mm-wave in 5G applications in HFSS are presented. The first example deals with an indoor communication scenario and the second deals with an outdoor communication scenario.

Indoor Wireless Communication Scene

Wireless communication between a 4x4 microcell (access point) array and an intended user at 60 GHz is studied in an indoor environment. In conventional beamforming techniques utilizing maximum ratio transmission (MRT), it is desirable that the beam be maximized towards a particular user equipment. However, this might also send a strong signal to other unintended wireless devices within the same environment. It is, therefore, important to reduce the transmission to the unintended devices, which can be achieved through zero forcing beamforming (ZBF) or null steering.

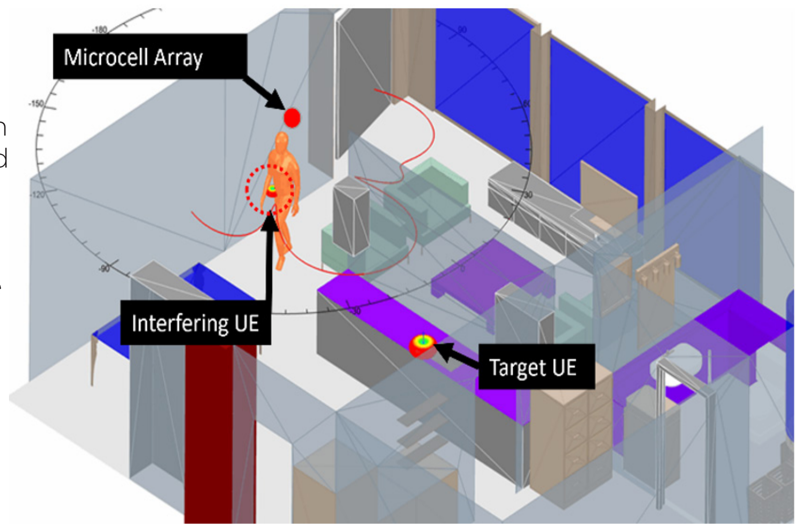

Figure 9. Indoor wireless communication scene

The microcell array is located on the wall of a room and intended to communicate with a target user equipment which is a printer inside the room (see Figure 9). The person walking in the room is carrying a phone that could potentially interfere with the communication channel between the microcell and printer. In this scenario, ZBF is used to dynamically steer a null in the direction of the phone while maintaining the main beam with peak gain in the direction of the printer. When the two coincide in angle from the array, the beamforming logic may choose a secondary multi-path angle to transmit energy to the printer, while placing a pattern null over the interference source. Thus, the microcell maximizes intended transmission to the printer while minimizing unintended transmission to the person's phone.

Outdoor Wireless Communication Scene

For the outdoor environment (Figure 10), a city model comprising buildings, cars, roads, sidewalks and pedestrians with user equipment is created in Ansys SpaceClaim and imported into HFSS where the appropriate material properties, boundary conditions and excitations are assigned. The microcell and user equipment are also added to the city scene in HFSS. Because this is an electrically large problem beyond thousands of wavelengths in size, using an FEM solver alone is not feasible for the entire problem. The versatility of HFSS allows engineers to apply different types of solvers to tackle diverse problems at hand. For a scenario in which the problem spans thousands of wavelengths in size, you have to use asymptotic ray tracing methods in a hybrid simulation. For the antenna array FADDM was used. To model the large communication channels in the apartment the ray tracer in HFSS SBR+ was used. In this approach, the problem is divided into subdomains that are efficiently solved using appropriate solvers and combined to create the final solution for the whole problem. The subdomains are the antennas, UEs and the large space in the apartment as well as the presence of other smart devices between the microcell array and the UEs.

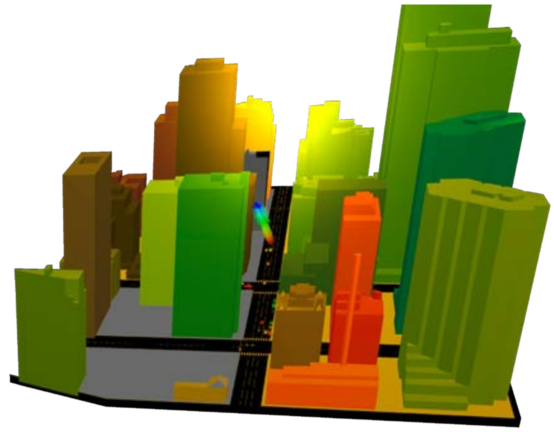

Figure 10. Electrically large wireless scene in an outdoor city environment

The system, composed of the 5G micro-cell array, channel and UE, is simulated using a combination of electromagnetic solvers. The micro-cell and UE are simulated using the HFSS FEM solver with each encapsulated in their own surrounding Huygens box and FEBI boundary condition. The resulting equivalent surface currents on the Huygens boxes are used as sourcing fields of an HFSS SBR+ simulation of the channel which uses an enhanced shooting and bouncing ray method for analysis. HFSS SBR+ is an extension of a physical optics (PO) technique which, through the tracing of rays from the respective source antenna models, “paints” electrical currents on the surfaces of the surrounding environments. These currents are then integrated over and coupled back into the equivalent surface current models from the HFSS FEM simulation to determine the phase coherent electromagnetic coupling between the devices. The resulting antenna-to-antenna normalized received power and phase provides the channel link between the micro-cell and UE.

In this way the 5G system modeling of a complex outdoor scene is accomplished.

/ Conclusion

Engineers can implement the comprehensive workflow described in this paper on Ansys EM simulation tools to analyze large, complex 5G antenna systems and their installed performance efficiently. They can use this design flow along with hybrid solutions in HFSS that utilize optimal analysis techniques at each scale of the problem. The workflow, along with the rigor and accuracy of Ansys HFSS, can help engineers create high-fidelity designs of antennas, arrays and microcells. Advanced capabilities in HFSS can help model MIMO systems, extract channel state information and simulate electrically large scenarios in busy city environments to understand the performance of the arrays, UE and communications channel.

Implementing the 5G infrastructure is going to be an enormous technological undertaking. Higher frequencies and the promise of higher performance of 5G means that advanced simulation tools are crucial for modeling total end-to-end wireless networks comprising phased array antennas installed on microcells as well as multiple user equipment all operating in urban environments.

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ANSYS, Inc.
Southpointe
2600 Ansys Drive
Canonsburg, PA 15317
U.S.A.
724.746.3304
ansysinfo@ansys.com