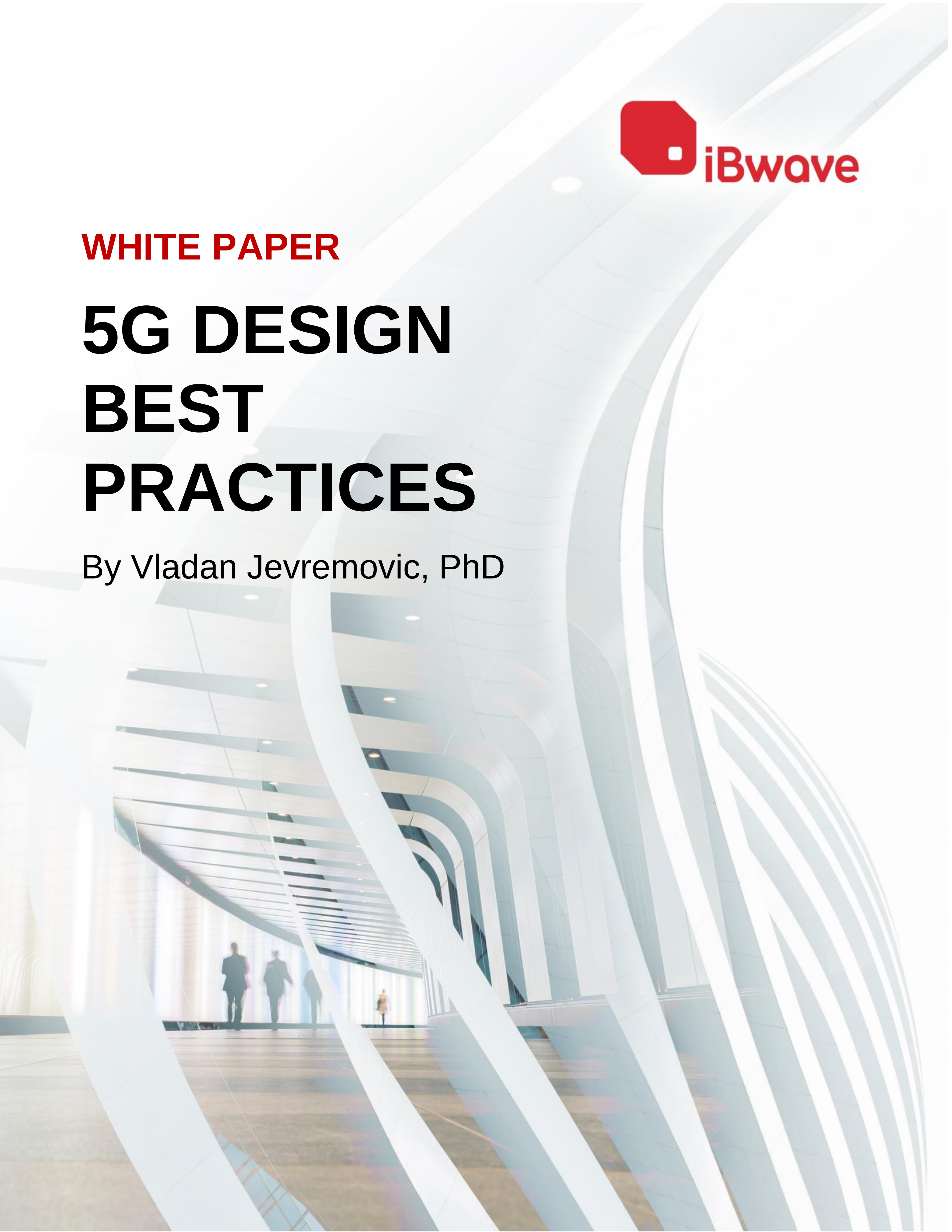

iBwave

WHITE PAPER

5G DESIGN BEST PRACTICES

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1 INTRODUCTION

5G Networks brought about a few major network design challenges when compared to LTE networks. Those challenges are mostly related to introduction of the high frequency band (above 24 GHz), and beamforming antenna arrays. The goal of this paper is to identify the challenges, and how to address them using iBwave Design, an indoor network design and planning tool.

2 DESIGNING 5G VS LTE: WHAT'S THE BIG DEAL?

2.1 THE MILLIMETER WAVE BAND (24 GHz AND ABOVE)

The simplest way to assess the impact of the high frequency band (also called "millimeter wave" band) on RF signal propagation and its range is to inspect Friis transmission formula. The formula gives us a relationship between the receive signal (P_r), the transmit signal (P_t), the distance (R) between the two, signal wavelength (λ), the receiver antenna gain (G_r) and the transmitter antenna gain (G_t):

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}$$

Where,
P_r = Power at the receiving antenna
P_t = Output power of transmitting antenna
G_t = Gain of the transmitting antenna
G_r= Gain of the receiving antenna
λ = Wavelength
R = Distance between the antennas

This equation is valid in Line of Sight (LOS) between the transmitter and the receiver. As frequency of operation increases, the signal wavelength decreases. If all other parameters are kept the same, doubling the frequency of operation reduces the receive signal by 6 dB. If the LTE network operates in AWS band (2.1 GHz), 5G network that operates at 28 GHz would have additional loss of $20*\log_{10}(28/2.1) = 22.5$ dB.

To make up for this additional loss, 5G millimiter wave networks rely on high antenna gain, both at the transmit and at the receive end. High antenna gain is achieved via beamforming, which also creates very narrow beams. These highly directional beams have higher gain than LTE directional antennas, which partially offsets the higher propagation loss. Another benefit of beamforming antennas is reduction in interference. Narrow beams isolate serving signal from interfering signals very well, which improves SINR and throughput. The downside of beamforming is incresed antenna circuit complexity, bigger antenna panel size, and greater power consumption.

However, despite the partial offset of the propagation loss, the high band 5G networks have much shorter range than the sub-6 GHz 5G networks. For that reason they are not used for blanket network coverage, but rather at high user density venues.

Best Practices: Use 5G millimeter wave networks at high-capacity venues. Use sub-6 GHz networks for blanket macro coverage.

2.2 UE 5G ANTENNAS

While there are many smart phone manufacturers, we are going to focus on two most common smart phone manufacturers: Apple (iPhone) and Samsung.

Information about iPhone 5G antennas is very scarce. Apple does not publish the antenna specs, so any information that is publicly available is from iPhone RF teardown reports, published by technology enthusiasts. One such report published in Microwave Journal [1] claims that iPhone 12 has two 5G millimeter wave antenna modules. One module is embedded on the side of the frame, and another on the back of the logic board. The report also states that those modules "look like a Qualcomm millimeter wave module […] as they [Qualcomm] are the only known manufacturer of these types of module". In Qualcomm's 5G presentation [2], UL millimeter wave link budget shows UE antenna array gain of 6 dBi. From antenna array theory, the 6 dBi antenna array gain corresponds to a 4-antenna array, as $10*\log_{10}(4) = 6$ dBi. Thus, we can conclude that iPhone12 has a couple of millimeter wave antenna modules, and each module has 4-antenna array with 6 dBi beamforming antenna gain. But, what about MIMO? Are those modules MIMO, and if so, are they 2x2 MIMO or 4x4 MIMO?

The two antenna modules are spatially separated. If antenna array in the first module has +45° polarization, and in the second module -45° linear polarization, then those two modules are two MIMO streams and we have 2x2 MIMO.

However, if each module has two collocated cross polarized arrays, one with +45° polarization and the other with -45° polarization, then we have 4x4 MIMO. In that case ¼ of the information is transmitted on +45° polarization in Module 1, another ¼ is transmitted on the -45° polarization in the same module, another ¼ of it is transmitted on +45° polarization in the second module, and the last ¼ is transmitted on -45° polarization in the second module. But is there enough separation between the modules to decorrelate the signals? Without the signal decorrelation, we cannot separate the +45° streams (or the -45° streams) from the first and the second module. It turns out that there is enough separation at millimeter wave frequency. The separation between the modules is only 4-5 centimeters, but at f=30 GHz that distance translates to 4-5 wavelengths, which is enough to decorrelate the signals of the same polarization. Thus, this antenna setup in iPhone12 is 4x4 MIMO with 6 dBi beamforming antenna gain.

Samsung is more forthcoming with its millimeter wave antenna information. In [3] they claim that Samsung phones have 4-antenna array with 7 dBi gain, and total of 4 streams. Thus, Samsung mmwave antenna is 4x4 MIMO with 7 dBi beamforming gain. This is comparable to iPhone12 antenna. It also confirms in an indirect way our assumptions about iPhone12 antennas because Samsung and iPhone have similar performance/features. In the same presentation Samsung also specifies horizontal and vertical beamwidth of their smartphone antenna.

It doesn't appear that sub-6 GHz RF modules at smart phones have beamforming antennas at this time.

Best Practice: In iBwave design, set UE antenna gain to 6-7 dBi when designing 5G millimeter wave networks. For sub-6 GHz 5G, we can keep the gain the same as for LTE UE.

2.3 BEAMFORMING MODELLING IN iBWAVE

5G eNodeB beamforming antenna patterns are created by large two-dimensional (planar) arrays. Typical arrays are 8x8, 16x16, or similar size. An 8x8 array is an 8x8x2 array, as each antenna location has two collocated linear polarized antennas: one with +45° and one with -45° polarization. Thus, an 8x8x2 array has 128 antennas; half of them create +45° linear polarization pattern, and the other half -45° linear polarization pattern.

From 5G theory, we know that Synchronization Signal Block (SSB) is always transmitted, and that each eNodeB SSB can have its own transmission slot, different from other eNodeB beams. This feature allows a UE to measure SSB signal strength at time slots where SSB signal is expected. These measurements are reported back to eNodeB, which then determines the optimum SSB beam for that UE.

The SSB Beams need more overlap amongst them because need to catch all UEs within eNodeB range. The beams that carry PDSCH signal need less overlap amongst them, because they need to minimize interference at UE. Consequently, SSB beams are wider than PDSCH beams.

As an example, we show PDSCH and SSB beamforming antenna radiation patterns:

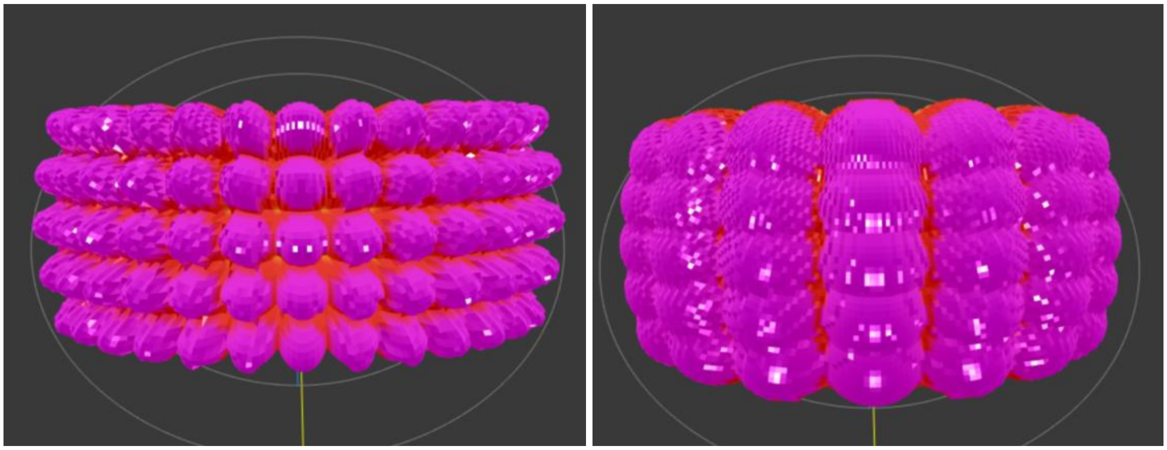


Figure 1: Beamforming PDSCH and SSB radiation patterns, side by side – MATLAB model

While SSB beams are not transmitted simultaneously, over time all of them transmit at least once, forming a following aggregate beamforming radiation pattern:

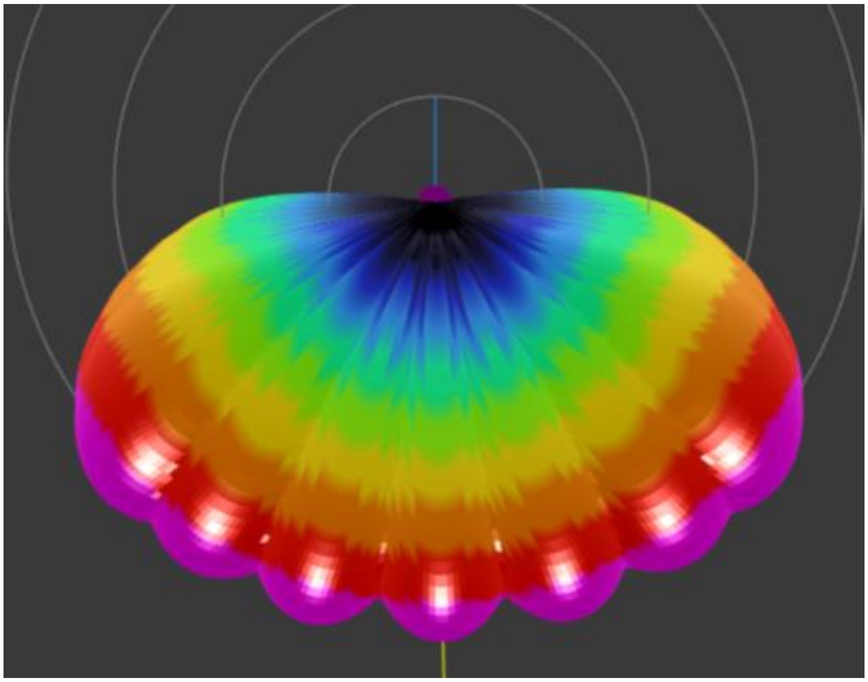


Figure 2: Aggregate 8x8 Beamforming radiation pattern, H plane – MATLAB model

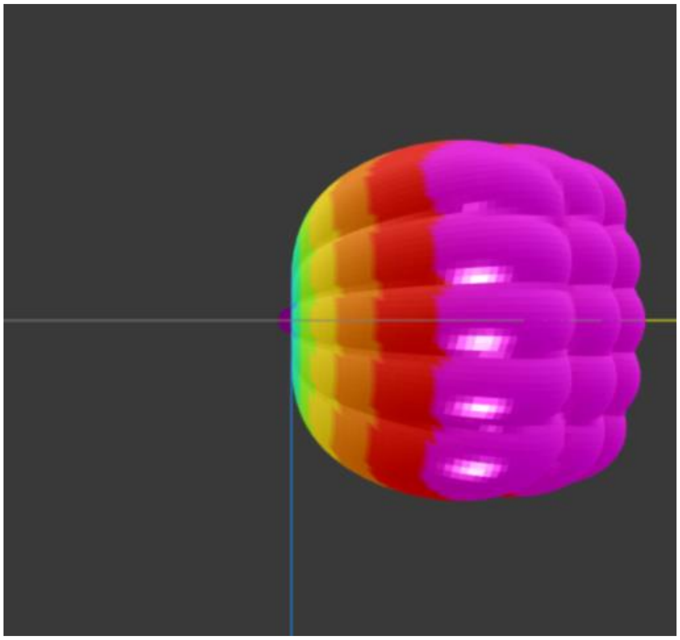


Figure 3: Aggregate 8x8 beamforming radiation pattern, V plane – MATLAB model

Aggregate beamforming radiation pattern is summation of individual SSB beams. As such, this aggregate radiation pattern is used to calculate SS-RSRP heat maps, which indicate eNodeB 5G signal coverage. Thus, SS-RSRP heatmap is KPI for 5G coverage, much like RSRP heatmap is KPI for LTE coverage.

In iBwave Design vex file we model aggregate SSB radiation pattern, as well as SSB and PDSCH individual beam radiation patterns. The former is used to calculate SS-RSRP, while the latter is used to calculate PDSCH SINR and MADR. A screen shot from iBwave .vex file illustrates this:

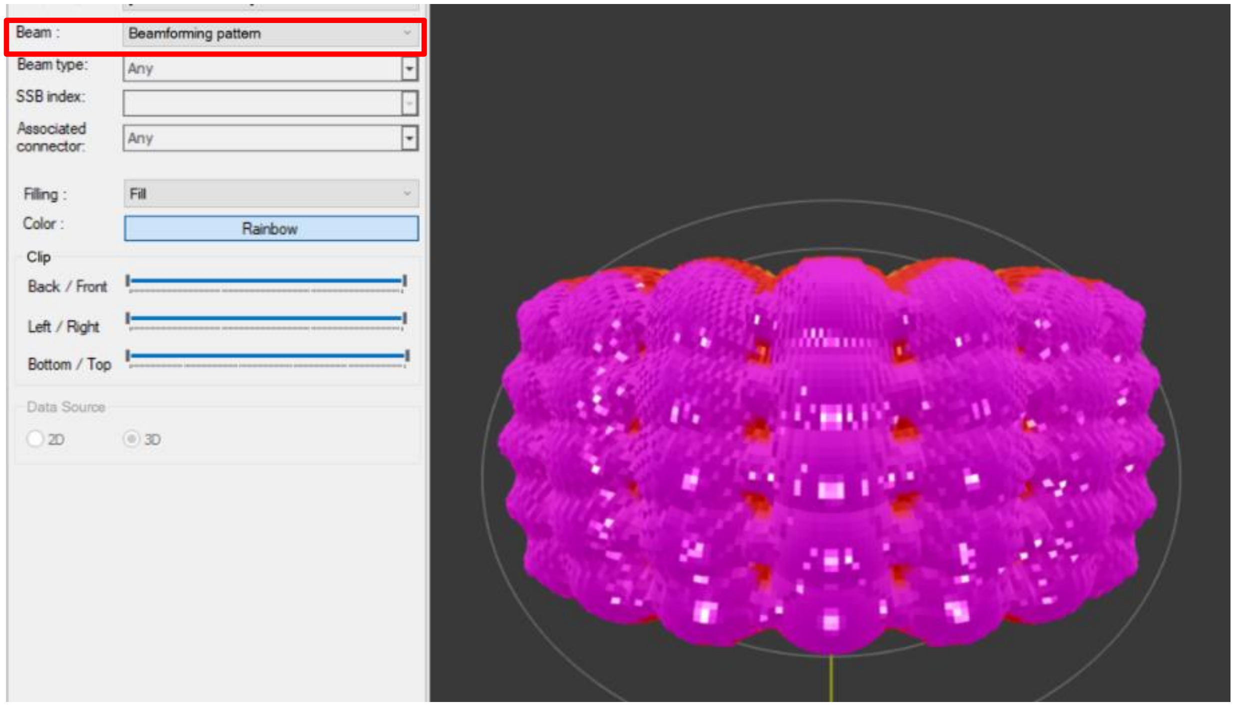

Beam : Beamforming pattern
Beam type: Any
SSB index:
Associated connector: Any
Filling : Fill
Color : Rainbow

Figure 4: Aggregate 8x8 beamforming radiation pattern in iBwave Design vex file – the MATLAB model

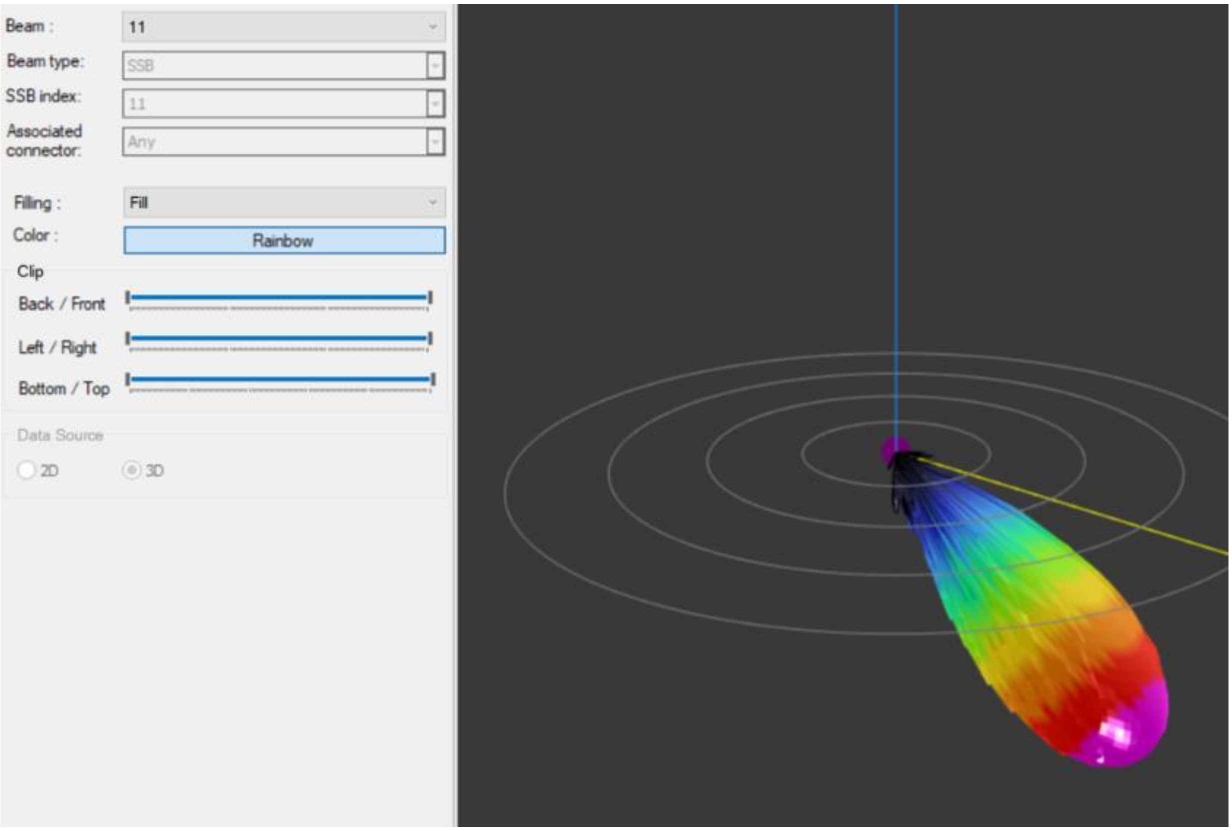
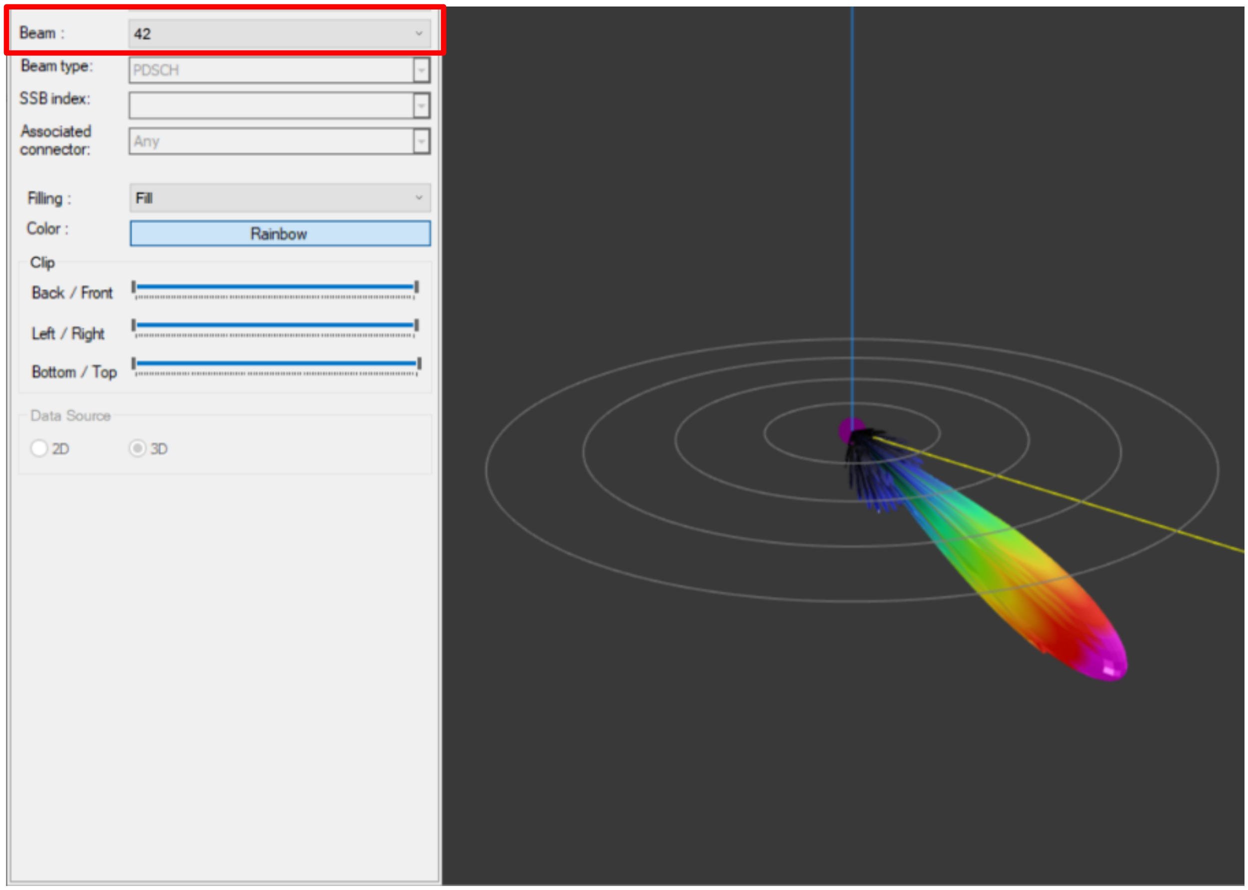

Beam : 11
Beam type: SSB
SSB index: 11
Associated connector: Any
Filling : Fill
Color : Rainbow

Figure 5: Individual 8x8 beamforming SSB radiation pattern iBwave Design vex file – the MATLAB model



Beam : 42

Beam type: PDSCH

SSB index:

Associated connector: Any

Filling : Fill

Color : Rainbow

Clip

Back / Front

Left / Right

Bottom / Top

Data Source

○ 2D ● 3D

Figure 6: Individual 8x8 beamforming PDSCH radiation pattern in the vex file – the MATLAB model

While we let OEMs model the aggregate the individual radiation patterns in small cell vex files, having both of them in vex file is not mandatory. However, both are needed in the file if we want to accurately calculate SS-RSRP and PDSCH-SINR, and consequently MADR. While our software would allow calculating PDSCH-SINR without the individual patterns in place, the resulting calculation would vastly underestimate PDSCH-SINR and MADR.

Best practice: Always check radiation patterns of 5G small cells by clicking on “view pattern”. From the “Beam” drop down menu verify that you can select “Beamforming pattern” and individual beams numbered 1,2,3…. If the numbered beams are not present in the drop-down menu, individual beams are not modelled, PDSCH-SINR and MADR cannot be calculated accurately, and PDSCH-SIRN and MADR heatmaps are inaccurate.

2.4 DOES SIZE OF AN OBJECT MATTER?

At sub-6 GHz, objects that contribute to penetration and reflection loss are walls, floors and ceiling and stadium seating areas. At sub-6 GHz, those objects are large compared to wavelength which guarantees specular reflection. The term “specular reflection” means that both the incoming and the reflected signals are planar waves, also called “rays”. If an object is small or comparable to wavelength incoming signal scatters when hitting such object, and there is not much signal reflection. That’s why we don’t need to model office furniture in sub-6 GHz networks.

At 30 GHz the wavelength is only 1 cm, so most objects are much larger than wavelength. This would imply that a very detailed modelling is required; for example, in an office environment all office furniture (chairs, tables, bookshelves, etc.) would need to be modelled. However, field measurements indicate that is not entirely the case. Significant reflection at 28 GHz was seen only from large whiteboards, mirrors, and flat screen TVs. We have not seen significant reflection from other objects in office environment. iBwave is working on measuring properties of those materials at 24-40 GHz and will include them in our database later this year.

Best practice: At millimeter wave, include large whiteboards, mirrors, and flat screen TVs in your floorplan model, as those objects reflect the signal well at millimeter wave frequency.

2.5 NEAR FIELD/FAR FIELD BOUNDARY

There are two radiation regions for EM wave away from antenna: near field and far field. A brief description for near/far field phenomenon is given in [4]. Technical term for the boundary between the two is called The Fraunhofer distance. This distance is calculated as $d = 2\frac{D^2}{\lambda}$. D is the largest dimension of the radiating antenna, and λ is wavelength of the transmitted signal.

Let’s assume that the diagonal of antenna panel is D = 0.5 meters. If we assume that the size of the panel is the same as the size of the planar antenna array behind it, then the Fraunhofer distance is:

d = 5.8 meters @ 3.5 GHz
d = 50 meters @ 30 GHz

However, we don’t know for a fact that the size of the panel is the same as the size of the planar antenna behind it. To verify that, we need to open the panel to inspect what is underneath. If we do that, we could see something like this:

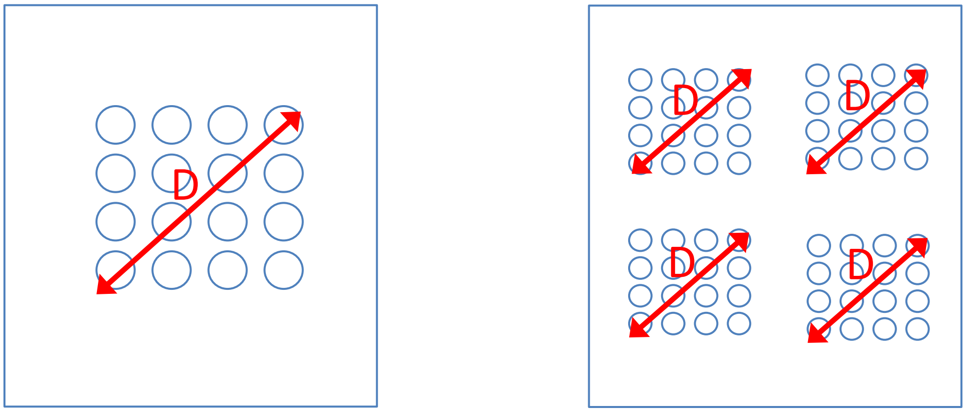


Figure 7: Two examples of the largest dimension D of planar beamforming antenna array, red arrow.

The figure to the left shows single planar array, while figure to the right shows 4 independent planar arrays. The latter generates four independent beamforming beams, each beam capable of serving a different UE. If UEs are well separated in space, this configuration increases capacity by a factor of 4, because the beams can transmit simultaneously. This configuration is feasible at millimeter wave frequencies, where each of the four arrays has D in the 10-15 cm range. Assuming D = 10 cm, the Fraunhofer distance is

d = 2 meters @ 30 GHz

If opening the panel is not feasible, the second-best method is to measure the Fraunhofer distance. This is done by measuring the receive power at predetermined distances, d = 1, 2, 4, 8... meters at antenna broadside. In the far field, received power drops 6 dB when the distance is doubled. Thus, if the power drops 6 dB between 2 and 4 meters, then the Fraunhofer distance is somewhere between 2 and 4 meters. If we want greater precision, we can make another set of measurements at 1.5 and 3 meters. If the signal drops 6 dB again, then the Fraunhofer distance is between 2 and 3 meters. If the signal drops less than 6 dB, then the Fraunhofer distance is between 3 and 4 meters. We can make more measurements in this manner until we determine the Fraunhofer distance with the desired precision.

Establishing the far field boundary is important because highly reflective objects in the near antenna field may significantly alter antenna radiation pattern. If the near field/far field boundary is at 2 meters, then the clearance around beamforming antenna should be 2 meters. This means that no highly reflective objects should be within the 2-meter radius around the antenna.

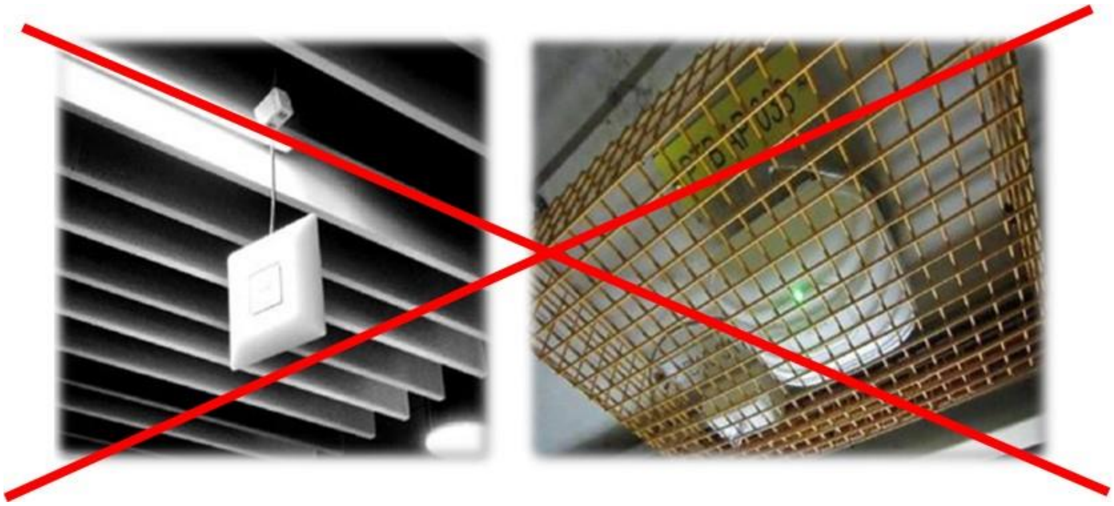


Figure 8: Highly reflective objects in the near field of an antenna.

Best Practice: Determine the Fraunhofer distance and pick antenna locations that do not have reflective objects within that distance.

2.6 EMF RADIATION COMPLIANCE

Beamforming antennas are highly directional antennas. Their gain is proportional to the number of antennas in a planar array. A planar array with 64 omnidirectional antennas with 0 dBi gain has beamforming gain of $10*\log_{10}(64) + 0$ dBi = 18 dBi. As indoor small cell/DAS LTE antennas are mostly omnidirectional with 2-3 dBi gain, the EIRP difference between the LTE and the 5G beamforming antenna is approximately 15 dB. However, the actual difference is less because beamforming antennas do not transmit at the same time. The difference between instantaneous and average 5G EIRP is, by conservative estimate [5], 6 dB, and therefore the delta between 5G and LTE EIRP is 15 – 6 = 9 dB. In [6], we show that adding beamforming millimeter wave antennas to an indoor network that already has multiband LTE signal may increase EMF radiation compliance distance by 110%. This drastic increase is solely due to 5G beamforming gain being much larger than LTE DAS/small cell antenna gain.

Best practice: Determine EMF radiation compliance while considering all bands/technologies in the network. As per Section 2.5, all independent planar arrays underneath a panel must be accounted for in EMF radiation compliance calculation. Set the compliance distance as an exclusion zone, which should be out of reach to public.

2.7 NON-LOS COVERAGE AT MILLIMETER WAVE FREQUENCIES

Most materials have high penetration and reflection loss at millimeter wave frequencies. Some light materials, like sheetrock, have penetration loss at the order of few dBs. Therefore, it is possible to have some NLOS coverage behind the first light wall at millimeter wave frequencies. However, the signal almost never gets past the second light wall.

As per Section 2.3, some objects that do not reflect signal at sub-6 GHz do reflect it at millimeter wave frequencies. Example of those objects are large screen TVs, large mirrors and large whiteboards. Those may be the source of non-LOS coverage where you don't expect it (behind a heavy wall, for example).

Best Practice: Pay attention to light walls (sheetrock) and objects with flat and smooth surfaces (whiteboard, mirrors, large TV screens) when modelling a venue that has millimeter wave network.

3 COVERAGE SCOPE LIMITATIONS

We can now summarize what we learned in Section 2 about signal propagation and 5G beamforming antennas at millimeter wave frequencies:

- There is High Line of Sight propagation loss due to high frequency.
- There is High penetration loss for most of in-building materials. Some light material walls can let the Non-LOS signal through.
- Some smooth surfaces reflect millimeter wave signal very well.
- The Fraunhofer distance sets the exclusion zone near antenna that should be clear of highly reflective objects.
- EMF compliance distance sets another exclusion zone, which should be out of reach to public.

The first two bullets limit the reach of millimeter wave coverage to Line of Sight or near Line of Sight only. While signal can pass through some light material walls, relying on NLOS signal for coverage is not a good practice.

The last two bullets, the Fraunhofer distance and the EMF compliance distance, need to be calculated prior to the site visit. Knowing them in advance helps to identify potential mounting locations. A lack of mounting locations that satisfy both requirements may limit the coverage scope; thus it is necessary to determine the potential mounting locations prior to finalizing coverage scope with the venue management.

Together, the first two and the last two bullets narrow down the coverage scope to areas with clear Line of Sight, and with enough clearance around antenna. Due to these limitations, the best design practice is to deploy 5G millimeter wave antennas to venues and/or hotspots with large capacity and clear Line of Sight, with enough clearance. Examples of venues/hotspots suitable for 5G millimeter wave antennas are stadium bowls, conference centers, hotel ballrooms, office conference rooms and office cafeteria. Designing 5G millimeter wave for ubiquitous coverage can be costly and is not recommended.

The third bullet reminds us that best design practice must include modelling objects that reflect the signal very well at millimeter wave frequencies. Failing to do so may underestimate both signal strength and overestimate SINR; the latter may cause unexpected drop in data throughput in areas with clear line of sight where we forgot to model those objects.

For sub-6 GHz band, only the last two bullets apply. Knowing the exclusion zones based on the Fraunhofer distance and the EMF radiation distance in advance to the site visit helps to identify potential mounting locations.

4 CONCLUSION

In this paper we presented the key differences between LTE and 5G networks. The differences are mostly due to higher propagation loss at high frequency and high beamforming antenna. The most design restrictions that are identified are at millimeter wave band. The best 5G indoor network design practices are outlined. Considering the scope limitation at millimeter wave band, our recommendation is to consider deployment of millimeter wave networks to venues where LOS propagation is predominant, and to hotspots with clear LOS.

5 REFERENCES

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