Design and Optimization for Mobile Networks in Stadium Environments

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***Abstract*— The main problem addressed in this paper is managing the growing demand for data-intensive applications while maintaining high-quality customer experience in a high capacity location. In a large venue like a stadium, a large number of people use their smartphones to share pictures and experiences, such as real-time video and download information. This behavior creates traffic profiles that differ from those typically seen in an ordinary day network, with higher uplink traffic and more frequent packet transmission. This dissertation has a starting point in the designing of an LTE network solution for stadium *José Alvalade*. The process of radio planning began by obtaining the 3D model of the stadium after doing a site survey. The selection and best mounting positions for the antennas were discussed, and the elements responsible for its operation presented for both a single-operator and multi-operator scenario. The capacity sizing theoretical background was exposed, and the number of sectors necessary to satisfy the nowadays traffic profile and the LTE subscribers was calculated, as so the number of resources needed to support each service type. Considering the 1800 and 2600 MHz band, simulations for measuring signal strength and noise, coverage areas, maximum achievable data rate, LTE overlapping and the needed mobile transmission power were performed and presented. The best solution found was considering 40 sectors for covering the seating area. 20 antennas were used being divided in two layers, both 1800 MHz and 2600 MHz band.**

***Keywords* — Growing Demand, High-quality Experience, Traffic Profiles, Radio Planning, Capacity Sizing, Simulations**

I. INTRODUCTION

The popularity of smartphones creates huge capacity requirements for the network during mass events that occur in big venues like stadiums. Today, everyone has a phone in their pocket and can share the event immediately on social media, changing the experience of events and the events themselves. A large number of people use their smartphones to share pictures and experiences, such as real-time video, and download information. The traffic is evolving to data-intensive applications like video. Counting as video traffic appears the use of embedded video in social media and web pages, this type of video traffic continues to grow increasing upstream data usage. These traffic profiles differ from those typically seen in the normal day network, with higher uplink traffic and more frequent packet transmission.

The growth in mobile traffic and the high quality of experience (QoE) that will be required in the next three to five years by the spectators, challenges operators to find a way of boosting mobile phone capacity and high-quality coverage in stadium environments. This dissertation seeks to find an optimum solution for a specific stadium environment by simulating different antenna models, adapting techniques and practises used before but now having in consideration the Portuguese spectators' characteristics.

The case study of this work is the stadium *José Alvalade*, located in Central Lisbon. Having in consideration that each case is different, and the solution is unique, a set of criteria are established in order to design the most efficient LTE network solution.

II. SITE SURVEY AND 3D MODELLING

After visiting the stadium, it was concluded that in terms of access for future maintenance and radio efficiency, the best location for mounting the antennas was on the existing footbridges located in the rooftop, shown in Figure 1. Each footbridge is above the beginning of the respective stadium tiers. This position helps separate the area of action in two tiers/rings, the antennas that are placed at the green footbridge will cover the lower tier and the others, placed at the yellow footbridge, will cover the upper tier.

In order to facilitate the future installation of the antennas, the center of the field and the middle of the goal were established as a reference to mount the antennas placed in the middle of the footbridges. The azimuth is the side to side direction that the antenna is pointed, refers to the rotation of the whole antenna around a vertical axis. Since, the blueprint of the stadium is geo-located only locally, the azimuth considered was based on the two reference points ignoring the fact that the magnetic compass will not give 0º in the considered direction. Having the middle ones position, the other antennas placed in both sides will have those as reference.

During the site survey, it was possible to observe that in the corner parts of the bleacher the seating area was closer to the rooftop than in the other parts of the stadium, so the yellow footbridge starts after the seating area finishes. For this reason, if the corner antennas were mounted in the yellow footbridge it would be necessary to force the rotation of the antenna to point to the lawn in order to cover the seating area. The problem is that in this situation the signal would reach the other side of the stadium (diagonal) overlapping signals, so mounting the antenna in the green footbridge was the only option to solve the problem.

Figure 1 - Photography taken during the site survey, identifying both footbridges.

A proper modelling of the venue is important not only for propagation analysis but to minimize the total costs, e.g. knowing the exact needed distance for materials like coaxial cables or fiber. After importing the CAD files to the iBwave Design Software, characteristics of the materials that constitute the venue were introduced in the tool, and inclined surfaces were identified. Stadiums are multilevel structures that contain different RF propagation environments. In this paper, only the seating bowl, i.e. the bleacher is studied. Through the advanced 3D iBwave modelling, a 3D model of the stadium was generated, considering the bleacher as an inclined surface. Figure 2 corresponds to the 3D model.

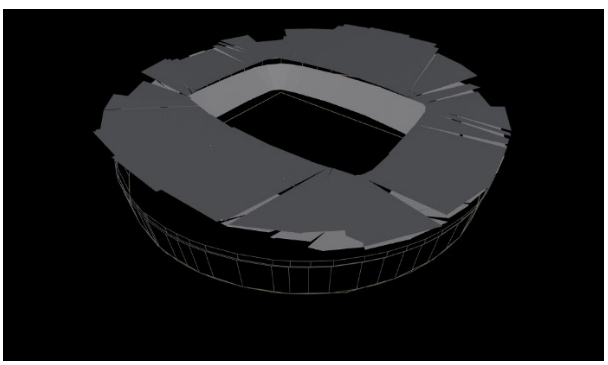

Figure 2 - Stadium 3D model extracted from the iBwave Design Software.

III. ANTENNAS SELECTION AND PLACEMENT

Knowing that for this type of high capacity locations, one of the biggest challenges is providing tightly gathered antennas with sufficient capacity and scope without causing interference, in this section, all the antennas mentioned are directional. This type of antenna radiates greater power in one direction so the antenna beam can be focused hence limiting the covered area in the size of a sector. These antenna type beam pattern suggest that the side lobes are very weak, causing little interference to the neighbouring sectors.

The yellow footbridge antennas are especially close to the stadium stand. For this reason, the antennas' radiation pattern is very confined in comparison to the ones positioned in the green footbridge. Therefore, a mixed choice of antennas is ideal, i.e., for each position, different characteristics are required so two different types of antennas will be used.

The first thing that is essential to have into account when choosing the antennas is the operating range of frequency bands. In order to increase the capacity, the antennas for this solution work at the 1800 and the 2600 MHz. The dual-band concept means that the antennas operate in two separate bands. For supporting Multiple-Input Multiple-Output (MIMO) 2x2, the antenna needs to have two ports for transmission (Tx) and two ports for receiving (Rx) for each band, if only has two ports the signals of both bands need to be combined before using directional couplers.

Since the antennas that will cover the first ring/ upper tier are farther away from the seats than the others, it is possible to take advantage of the fact that the radiation pattern is not so confined. Owing to the higher number of users and the ring shape the most suitable antenna will have ideally the same degree values for the vertical and horizontal beamwidth. The CommScope CNLPX3055F presents an almost squared radiation pattern. The overlap between cells causes interference, so the area covered by the antenna beams side lobes should be minimized. This antenna was specially designed for stadium environments offering narrow beamwidths that can be reliably shaped into sectors supporting all users without signal overlaps. After doing the simulations, this antenna model was chosen for all the positions except two. For the position of the antennas B7 and B17, better results were obtained with another antenna model from CommScope.

The first simulation (simulation 1) was made, using in all positions the CommScope antenna model, specially designed for stadiums. However, the relation between signal and noise-interference was not the desired one in the upper tier/level B of the bowl, as shown in Figure 3.

Consequently, the higher throughput value was achieved in a smaller part of the stand, when comparing to the lower tier/level A. These results are reflected in the legend of percentages presented in Figure 4. In level A, 71.1% of the bleacher achieves the higher data rate value against the 48.4% achievable in level B.

By analyzing the output maps above, changes need to be done at the level B. The CommScope model was the best option again in the taller part of the grandstand. In that part of the stadium, the bleacher is constituted by more seats, so more users. Using an antenna with a larger horizontal beamwidth than the stadium designed one, the resulting sector would be responsible for covering a large number of users comparing to other sectors, in logical terms that is not desirable.

Having in mind that the number of users covered should be identical for every sector, that the interfering zones must be minimized and that the stadium designed antenna presented great characteristics, simulations started to be done changing only the antennas position and the respective azimuth. However observing the changes that occurred in the output maps when changing only the position and the azimuth of the CNLPX3055F antenna, it was concluded that the antennas behind the beacons, antennas B7 and B17, should have a narrower beamwidth in order for the signal not overlap the one emitted by the corner antennas. That is when the antenna CMAX-3030S-D-V53 was tested and chosen for the best results and the balance between the output maps from both levels/tiers.

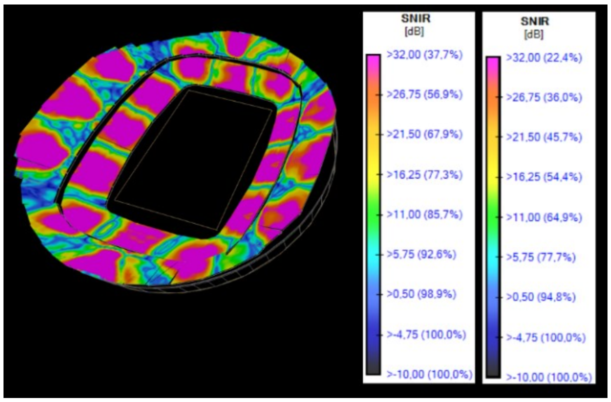

Figure 3 - *iBwave SINR output map considering the 1800 MHz band (simulation 1).*

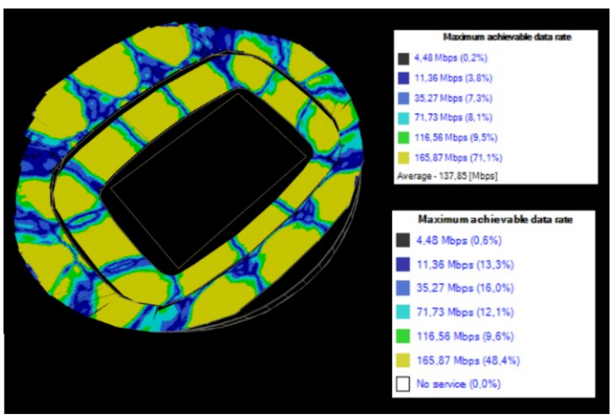

Figure 4 - iBwave MADR output map considering the 1800 MHz band (simulation 1).

For example, by observing Figure 5, is possible to verify that the percentage of seating area where the signal is not overlapping is very similar between levels, in level A 91.3% and in level B 90.1 %.

Table 1, presents the configuration considered for the final solution antennas, shows the azimuth and the tilt defined for each antenna. Both results were chosen based on simulations.

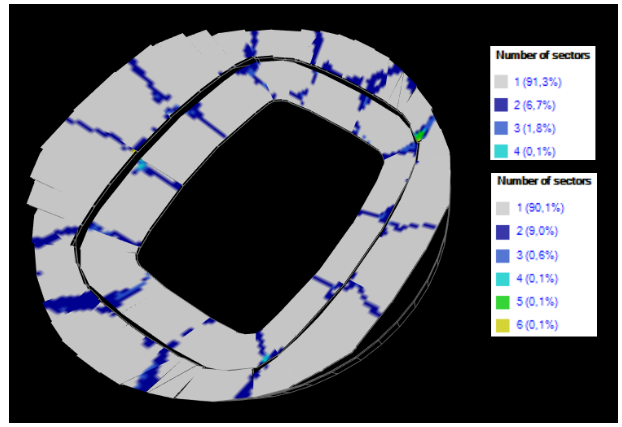

Figure 5 - Final simulation iBwave LTE Overlapping output map considering the 1800 MHz band.

Table 1 – Final Solution antennas configuration.

Antenna	Sector	Antenna Model	Azimuth (degree)	Tilt (degree)
A1	1	CNPLX3055F	180	60
B2	2	CNPLX3055F	180	20
A3	3	CNPLX3055F	185	60
B4	4	CNPLX3055F	230	10
A5	5	CNPLX3055F	240	40
A6	6	CNPLX3055F	270	60
B7	7	CMAX-3030S-D-V53	270	20
A8	8	CNPLX3055F	310	45
A9	9	CNPLX3055F	355	65
B10	10	CNPLX3055F	310	10
A11	11	CNPLX3055F	0	65
B12	12	CNPLX3055F	0	25
A13	13	CNPLX3055F	60	5
B14	14	CNPLX3055F	55	10
A15	15	CNPLX3055F	65	35
A16	16	CNPLX3055F	90	60
B17	17	CMAX-3030S-D-V53	90	20
A18	18	CNPLX3055F	120	45
A19	19	CNPLX3055F	175	60
B20	20	CNPLX3055F	130	10

Based on the stadium morphology, the number of sectors calculated in section VI and after all the simulations done using the iBwave Software, the ideal position to mount the chosen antennas was the one represented in Figure 6.

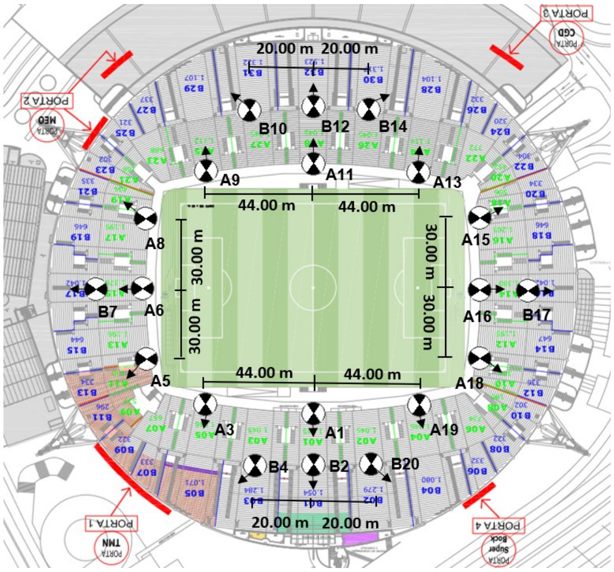

Figure 6 - Antenna final position scheme.

IV. RADIO INSTALLATION POINTS

The creation of basic infrastructure to the installation of equipment, as well as, all the elements that support its operation must be taken into account. For this reason, there will be 12 radio installation points (RIs) that need to guarantee energy, transmission and Radio Frequency (RF). Each RI will be composed by radio remote units (RRU's), coaxial cables, optical fiber, power points (PPs), rectifiers and optical distribution frames (ODF´s) per operator.

If in this work, the three operators were taken into account, for the LTE solution, there will be 6 RRU's per antenna, 2 per operator if each band uses a different radio (separated hardware). In the case of the radio model support, both 1800 MHz (B3) and 2600 MHz (B7) band (same hardware), there will be 3 RRU's per antenna, 1 per operator. Each RRU communicate with the baseband unit (BBU) through an optical fiber, per one RRU-BBU connection are required two optical fibers, so per antenna 12 pars of optical fiber are necessary in the first case and a half in the second case. Since both B3 and B7 band combination is not usually to appear in the same radio equipment, different hardware was considered for each band. Coaxial cables always make the connection between the radio equipment (RRU) and the antennas, for that reason the 6 RRU's per antenna are placed a meter apart from the antenna so that the losses are negligible.

In order to ensure MIMO 2x2, for both sectors, the use of a directional coupler is mandatory, at least when considering the CNLPX3055F antenna since only has 2-ports. Knowing that each radio "feeds" an antenna input port, it is necessary to have at least two 2:1 directional coupler to combine both signals into one output signal that connects to the input port of the antenna. So, the frequency range of the combiner needs to encompass the 1800 MHz band in one input port and in the other the 2600 MHz band. If a 2:1 combiner option is not possible, the second option is to use a 2:2 combiner.

V. MIMO TECHNIQUE

MIMO stands for Multiple Input Multiple Output, where multiple refers to multiple antennas used simultaneously for transmission and reception. Using the multipath signal propagation, that is present in all terrestrial communications, MIMO is used to improve communication performance, offering significant increases in data throughput and link range without using additional bandwidth or transmission power [1].

The limit to how much data can be transmitted in a given bandwidth is known as the Shannon-Hartley theorem (Shannon's Law), the channel capacity (bits/s) can be calculated by:

$$C \approx n \times B \times \log_2(1 + \frac{S}{N}) \qquad (1)$$

Where:

- n is the number of Tx/Rx antennas;
- B is the bandwidth in Hz;
- S/N is the signal-to-noise ratio.

According to [2], MIMO and its usage, there is a significant boost to the number of transmitted information bits, improving the system throughput and spectral efficiency. Applying the definition of MIMO nxn directly to equation (1) means increasing the theoretical maximum data transfer speed n times when compared to the use of single-input-single-output (SISO).

The existence of multiple antennas in a system means existence of different propagation paths. Aiming at improving the data rate of the system, the spatial multiplexing method is used, since different portions of the data are placed in different propagation paths. This technique consists in sending signals from two or more different antennas with different data streams. The receiver can distinguish between the various paths and extract independent data streams from each when processing the signals, increasing the peak data rates by a factor of 2 (2x2 configuration).

The more antennas the UE has, the more data can transfer at once, that means faster wireless download and upload speeds. To achieve these faster speeds, it requires that the user is connected with a cellular network that supports 4x4 MIMO. However, only UE belonging to category 5 upwards can support 4x4 MIMO. A UE with low modulation schemes cannot take full advantage of this MIMO configuration. This variation of MIMO is now standard on high-end phones which corresponds to a small number of smartphones models. Most UE cannot achieve high modulation schemes like 256-QAM, only the ones categorized 10 forwards can and most of the time only in downlink connections. So, the expression "the more MIMO, the better" is not applicable when the UE is connected to a cellular network that offers more MIMO but does not support this type of system.

In stadium environments, it is crucial to think not only in terms of the best theoretical solution but in terms of reaching and providing a good QoE for the biggest number of users. It is important to mention too, that a user that can reach this high modulation (256-QAM) occupies a big part of the band “stealing” from other users that are not capable. Nowadays not only for a question of fairness but of costs too, a 2x2 MIMO system was chosen.

VI. SECTORIZATION AND TRAFFIC PROFILE

Sectorization has a dual purpose in the design of a radio network, increasing network capacity and minimizing the number of signals present in the area by limiting sector coverage. There are three sectorization types: horizontal, vertical and mixed sectorization that corresponds to hybrid horizontal-and-vertical sectorization. Limiting the coverage also limits interference from non-serving sectors, which improves capacity, signal-to-interference-plus-noise ratio (SINR) and maximum achievable data rate (MADR). In Line-of-Sight (LOS) areas like the seating bowl, sector overlap minimization is achieved by using highly directional and isolated antennas.

Since stadium, *Estádio José Alvalade,* is partly covered by a roof and has a different number of seats in the two levels/rings of sectorization it is not sufficient to use horizontal sectorization. The number of seats at the lower tier (level near the field) is superior to the ones existing at the upper tier. A vertical sectorization will be a better choice to mitigate the different quantity of users on both levels due to its type of coverage. However, the most efficient and expensive too will be the mixed sectorization. For this solution, a mixed sectorization was selected.

The number of sectors per carrier depends on the number of seats, the carrier’s subscriber penetration rate and the carrier’s mobile traffic profile. The case study stadium has 50 095 seats distributed by two different levels. In order to not emphasize one of the three mobile network operators in Portugal: MEO, NOS or Vodafone, a subscriber uniform market share was considered, so each operator has 1/3 of the total seats. It is important to have into account that not all terminals support LTE technology, the 4G penetration percentage is about 70% in Portugal UEs, value revealed by Dense Air at the Small Cells World Summit 2019 in London [3].

According to [4], to understand the total number of sectors that should cover the seating area is important to follow some steps. First, a calculation for the maximum number of LTE subscribers inside the stadium is required: 50 095 is the total capacity/number of seats, 1/3 of this is approximately 16 699 seats. Giving a margin of growth until October, an 80% penetration rate was applied to this number; there will be 13 360 LTE subscribers per operator.

Secondly, the MIMO data rates considered were taken from both SINR, and MADR output maps, obtained when simulating the chosen solution and they are used to obtain the average data rate per sector. Table 2 resumes this step.

Table 2 - Coverage (%) distribution of MADR per modulation based in the final solution SINR and MADR output maps.

Modulation	MADR (Mbps)	Coverage (%)
QPSK	11.36	4.6
16-QAM	35.27	8.4
64-QAM	71.73	9.7
64-QAM	116.56	11.15
64-QAM	167.87	66.15

$$datarate_{average} = 11.36 \cdot 0.046 + 35.27 \cdot 0.084 + 71.73 \cdot 0.097 + 116.56 \cdot 0.1115 + 167.87 \cdot 0.6615 \approx 133.16\ Mbps$$

According to [5], in order to UEs reach the theoretical peak data rates, different conditions must be fulfilled, including the UE being the only one active in that sector. Of course, this condition will never be achievable at an event situation. Knowing this, the coverage is based on the maximum achievable data rate (MADR) values obtained with the iBwave Software, Figure 7. From these values, the $datarate_{average}$ was calculated and used to obtain the necessary number of sectors. The highest data rates (165.87 Mbit/s) are only possible near the antenna. The lowest data rates (11.36 Mbit/s) will be where the sectors overlap. And the reasonable data rates will be where the signal is not as strong as in the direction of the antenna but is not an overlapping zone.

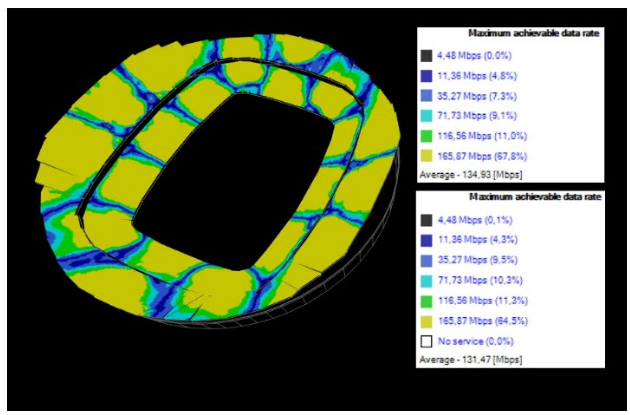

Figure 7- Final Solution iBwave MADR output map considering the 1800 MHz band.

Contrary to what happened in outdoor situations, where traffic is considered for the different distribution of calls typical over the day, week and longer cycles; for stadium environments traffic is always designed for the maximum stadium capacity. To ensure that it reaches close to all the expected demand [6].

The book [4] presents the duration of the network connection during a busy hour and the fixed data rates in kbps based on a user profile in a stadium environment. However, these values are not considering the today typical social networking service (browsing, file sharing and video streaming). For this reason, the values for data rates considered are the ones presented in Table 3. A downlink performance was considered. It is important to note that a subscriber can use more than one service type per busy hour at a stadium environment. The average duration of video conferencing session is shorter than other venues due to crowd noise. The value assumed for video streaming was not the typical average data rate (5120 kbps) since the video traffic appears embedded in social media and web pages. These web applications are built in order that a sufficient quality for video streaming can be achieved with 2000 kbps of data rate.

Table 3- Average data rate [kbps] per type of service (based on [4] and [7]).

Service		Service Class	Average Data Rate [kbps]
Voice		Conversational	12.2
Email		Background	100.0
Web Browsing		Interactive	500.0
File Sharing		Interactive	1024.0
Data Download		Interactive	1000.0
Social Networking		Interactive	384.0
Video	Calling	Conversational	384.0
	Streaming	Streaming	2000.0

According to [8], the best way to estimate traffic in the network is in terms of 'erlangs'. The amount of traffic generated by a user in one traffic channel for a busy hour. When a user generates 25 mErl of traffic during the busy hour is the equivalent to 120 seconds of network usage, i.e., 2 minutes. One Erlang means that a single circuit is used 100% of the time [6]. The connection duration considered was based on personal experience.

The blocking rate is the percentage of attempted network connections that are denied due to insufficient network resources. In data, connections request is never denied, for this reason, there is a margin license connection for users which limits the entrance of users in each carrier. More users will degrade the cell because the connection will be delayed until resources are not available. This delay will give customers the perception of a “slow” network. If the blocking rate is efficient, a higher wireless utilization rate would be obtained. However, the aim is to guarantee the best possible QoE, so the blocking rate is low. Table 4, shows the connection duration, the data rates and the desired blocking for the different types of services.

Duty cycle is defined as the ratio of carried traffic to theoretical maximum traffic when all resources are used for the full hour. Since the carried traffic corresponds to the traffic intensity handled, in a peak situation the cell is loaded, more PRBs are used, so a low value for this parameter was considered, 10% in this study. In this LTE capacity calculation, it was assumed that data is transmitted to each user only once in the LTE frame. Therefore, a subscriber receives that every 10 ms. So, the delay between two consecutive data Tx will be 10 ms, and the transmission duration is 1 ms.

Table 4 –Data Traffic Distribution at the stadium during the busy hour per service type.

Type of Service	Connection Duration (mErl/user)	Data Rate (kbps)	Blocking rate (%)
Email	12.5	100	1
Web Browsing	37.5	500	2
Video Calling	5	384	1
Data Download	50	1000	2
Video Streaming	37.5	2000	4
File Sharing	50	1024	2
Browsing	75	384	2

Once again, according to [4], the required data throughput per service type is calculated using the expression and presented in Table 5:

$$Throughput_{service} = LTE_{Sub} \cdot \frac{Connection_{duration}}{1000} \cdot \left(1 - \frac{Blocking_{rate}}{100}\right) \cdot \frac{data_{rate}}{1000} \cdot \frac{Tx_{delay}}{duty_{cycle}} \quad (2)$$

Where:

- LTE_{Sub} is the number of LTE subscribers per operator;
- $Connection_{duration}$ is the duration of the connection in mErl/user;
- $Blocking_{rate}$ is the desired percentage of blocking per service type;
- $data_{rate}$ as the name indicates is the data rate per service type in kbps;
- Tx_{delay} is the delay between consecutive data transmissions (Tx);
- $duty_{cycle}$ represents the duty cycle, and it is always 0.1.

Table 5 - Results obtained from the expression (2).

Type of Service	Throughput (Mbit/s)
Email	16.53
Web Browsing	245.49
Video Conferencing	25.39
Data Download	654.64
Video Streaming	961.92
File Sharing	670.35
Browsing	502.76

$$Throughput_{total} = 3077.08\ Mbit/s$$

Considering the distribution of MADR from Table 2, the number of sectors necessary to obtain the required total throughput is:

$$\frac{Throughput_{total}}{datarate_{average}} = 23.11 \approx 24\ sectors \quad (3)$$

In order to guarantee a good QoE for the spectators, 24 sectors are necessary. However, the design and implementation of a dedicated solution for a large venue, like the case study, implies a considerable investment cost so it cannot be implemented only for nowadays traffic characteristics. The solution needs to be designed in order to make the investment profitable for as long as possible. For this reason, the users will be distributed by 40 sectors.

VII. SINR

The performance of any radio channel is not only related to the absolute signal level, but also the quality of the signal. When there are active communications between the base stations (BSs) and the users equipment (UEs), the interfering power is considered, and the SINR is used to determine the radio channel conditions for a given UE.

For LTE capacity dimensioning, an LTE SINR coverage map was calculated in iBwave Software. When considering the specifications written above as the final solution, a SINR coverage map was simulated, and the stadium bowl can be split into 5 SINR ranges with different efficiency (bits/RE), as shown in Figure 8. The prediction legends on the right side of the picture are for level A, and the one on the left is for the level B. This simulation was obtained using the 1800 MHz band.

The relationship between SINR, modulation scheme and spectral efficiency taken from Table 6, enable us to calculate the number of resources needed to support each service type listed for busy-hour traffic at stadiums. LTE resources are Physical Resource Blocks (PRB). The number of resources needed varies with SINR.

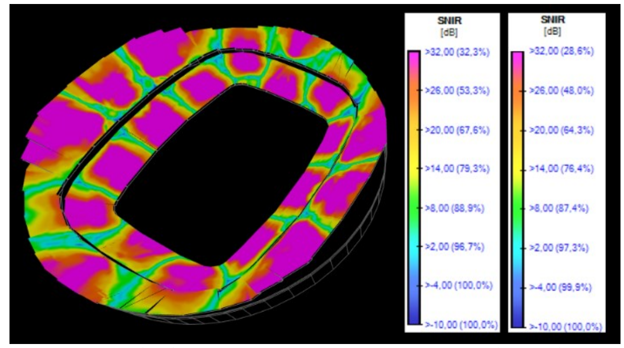

Figure 8 - Final solution iBwave SINR output map considering the 1800 MHz band.

The mathematical expression used to calculate the instantaneous data rate of each user is:

$$R\ (t) = Efficiency\ (t) * RE\ /\ RadioFrame_{length} \quad (4)$$

Where:

- R is the instantaneous data rate at time t (bps);
- Efficiency corresponds to the spectral efficiency (bits/RE) – Table 6;
- RE is the total number of REs specified for downlink data transmission;
- $RadioFrame_{length}$ is 10 ms because it was assumed that data is transmitted to each subscriber only once in each LTE frame.

Knowing the data rate for each type of service Table 4 and the spectral efficiency tabulated in Table 7, the total number of Resource Elements (REs) needed for the downlink data transmission can be easily obtained.

According to [2], with the typical cyclic prefix, a PRB contains a total of 168 resource elements (RE). Each PRB has 148 resource elements for 10% Block Error Rate (BLER) threshold, and 20 REs are used for control and signaling purposes. With this reference number of RE per PRB and the number of REs obtained from the expression (4), the number of necessaries PRB is known, Table 6. It is important to have into account that if SINR is high, a single PRB may be enough to support a type of service. If SINR is low, more than one PRB may be required.

The efficiency (Bits/RE) values were calculated using averages based on Table 6. For Range 1 (R1), 0.5125 bits/RE was considered, for Range 2 (R2), 1.5222 bits/RE, for Range 3 (R3), 2.8197 bits/RE and Range 4 (R4), 4.5136 bits/RE. The efficiency value for Range 5 (R5) was directly extracted from Table 6, 5.5547 bits/RE. Where R1 is between $-4 \leq SINR < 2$, R2 between $2 \leq SINR < 8$, R3 between $8 \leq SINR < 14$, R4 between $14 \leq SINR < 20$ and R5 between $20 \leq SINR < 32$.

Table 6 -Look-up considering 10% Block Error Rate (BLER) threshold (adapted from [Basil17]).

Range of SINR (dB)	Modulation	Efficiency (Bits/RE)
SINR < -6.936	Out of Range	--
-6.936≤SINR<-5.146	QPSK	0.1523
-5.147≤SINR<-3.18	QPSK	0.2344
-3.18≤SINR<-1.253	QPSK	0.3770
-1.253≤SINR<0.761	QPSK	0.6016
0.761≤SINR<2.699	QPSK	0.8770
2.699≤SINR<4.694	QPSK	1.1758
4.694≤SINR<6.525	16 QAM	1.4766
6.525≤SINR<8.573	16 QAM	1.9141
8.573≤SINR<10.366	16 QAM	2.4063
10.366≤SINR<12.289	64 QAM	2.7305
12.289≤SINR<14.173	64 QAM	3.3223
14.173≤SINR<15.888	64 QAM	3.9023
15.888≤SINR<17.814	64 QAM	4.5234
17.814≤SINR<19.829	64 QAM	5.1152
SINR≥19.829	64 QAM	5.5547

Table 7 - Number of PRBs needed per connection on the ranges obtained from the iBwave SINR output map (Figure 8).

		Number of Physical Resource Blocks (PRB) per connection				
Service Type	R(t) (kbps)	R1	R2	R3	R4	R5
Emails	100	12	4	2	1	1
Video Conferencing	384	45	15	8	5	4
Social Networking	384	45	15	8	5	4
Web Browsing	500	58	20	11	7	5
Data Download	1000	116	39	21	13	11
File Sharing	1024	119	40	22	14	11
Video Streaming	2000	232	78	42	26	21

VIII. LOAD BALANCING

One of the most critical aspects when designing a network is the distribution of load over the network. It is necessary to take into account that putting an antenna per used band is quite tricky: too much weight in the infrastructure because of all radio equipment and cables, maintenance will be more demanding, and the price would be much higher. The best way to reduce the number of antennas installed is by creating two LTE layers. So instead of having two antennas, the stadium has one that uses a mechanism called Load Balancing (LB). Not all UE behave in the same way before the different frequency bands. So, load balancing has to be done so that in peak situations, everyone has the same level of user experience, whether using a more demanding application or not.

There are two ways of making the load balancing between LTE 1800 and 2600 band:

1. By the number of PRBs being used;
2. By distributing the number of users equally per each band.

In an outdoor network, the indoor penetration of frequencies, such as the band 800, 1800 and 2600 is different (for propagation reasons). So the distribution is made based on the PRB status since the eNodeB knows if the PRB is: being occupied/allocated or free, which involves transferring users from the layer with less free PRBs to the one that has more available resources. However, in stadium environments, more specifically in peak situations like half-time, all PRBs are being used so this balancing option will not be efficient. For this reason, the distribution is made based on the number of users in each band. The BBU has the LB parameterization loaded and is responsible for counting how many users are in one band and the other. How does BBU know this? When the Mobile Terminal (MT) makes an RRC connection setup (that is, establishes an uplink connection - example: when it refreshes a web page) starts counting as a user in that frequency band. The number of users must be equal in both 1800 and 2600 band.

According to [9], the load balancing techniques may be based on the active or idle mode users. The big difference between the two modes is the mobility procedure carried out when real-time traffic or QoS demands increases in a cell. In idle mode, there will be a cell reselection: natural if the mobile terminal (MT) changes its spatial location and the MT loses the cell signal or forced. In stadium environments needs to be forced since the antennas are in LoS and very close to the bleacher (seating area) so the signal is always strong. In active mode there a handover would take place.

The cell reselection is a slower process than the hard HO since it does not need to give such a fast response, involves much less signaling and synchronism. This is reflected in the number of occupied PRBs. In the moment of transition from one cell to another, the user doing the HO will count as two, one in the cell that he is abandoning and the other in the destination cell. Since less free PRBs available are reflected in slowness and the objective is to balance the cell load the more efficient way, is to do Inter-Frequency Load Balancing (IFLB) in idle mode instead of active mode.

When a user is camped in a cell and sends a message with an application starting from the moment it waits for the answer and leaves the application running in the background, it may enter in idle mode. How? The BBU can be defined to after 10 seconds with low throughputs to force the UE to idle mode. This acceleration of the transition from active to idle mode is desirable since it was defined that the

LB will occur in idle mode and that with fewer users in active mode the eNodeB is free for new users to enter.

IX. SIMULATIONS

The first simulation made was using only the CommScope antenna, designed especially for stadiums, the CNLPX3055F model. However, it is possible to observe in

Figure 2 and Figure 3, which for the level B/upper tier, this solution was not so good. So, the main goal was to improve the results obtained in the upper tier without degrading the ones obtained for the lower tier. Identical output map values for both stadium levels were the results to achieve.

As explained before, the antennas covering the corners are closer to the seating area when comparing to other parts of the bleacher. So, to cover both the upper and lower tier, the antenna must present a big vertical beamwidth (VB). For this reason, a second and third simulation were performed using different antenna models with a wider vertical beamwidth than the stadium antenna. For simulation 2, the corner antenna model used was the CommScope CMAX-DMH60-43-V53 and for simulation 3 was the JMA XGU-FRO-130.

When comparing the RSRP output maps, it was possible to observe that the signal strength level is higher and more uniform in simulation 2 than in simulation 3. These results can be justified by the differences between both antenna models characteristics. Despite having a similar VB for the 1800 band, the CommScope antenna presents a 68 degree horizontal beamwidth (HB) versus the 32 degrees of the JMA antenna. This results in a higher signal strength level in the corners, higher SINR values and, consequently, bigger MADR for level B resulted in an average of 121.53 Mbps for simulation 2 versus 109.79 Mbps for simulation 3, considering 1800 MHz band. Using the 2600 band, the RSRP Output Maps present drastic differences from one simulation to the other. This happens because both JMA antenna VB and HB are smaller than the beamwidth values of the CommScope antenna. The signal strength level difference is more visible in the corners, especially on level A, which reflects on the lower average values of MADR. Although the difference between is not so accentuated as expected, this may be justified by the high gain value of the JMA antenna.

One of the most relevant simulations resulted from using a discontinued antenna model CMAX-DM60-CPUSEi53 for the corner antennas, and the best results were obtained. However, with the same configuration and conditions, the output maps using the actual antenna model CMAX-DM60-CPUEV53 were noticeably worse. Analyzing both antennas datasheets, most parameters were similar; however, the actual antenna front-to-back ratio was 3 dB lower. This parameter should have the highest possible value because of the rooftop characteristics.

After this disappointing result, the closest simulation to the results obtained in that failed attempt (simulation 5) were the ones obtained with the final solution. Although the chosen solution was not so balanced between the results using both bands as simulation 5 since the front-to-back ratio varies from one band to the other.

The RSRP output maps differences, Figure 9 and Figure 10, are justified by the 3 degree difference in the HB and the 1 degree difference in the VB. The close proximity of the antenna to the users confers relevance to broader beamwidth values in order to accentuate the effect of the radiation pattern and consequently the signal strength level.

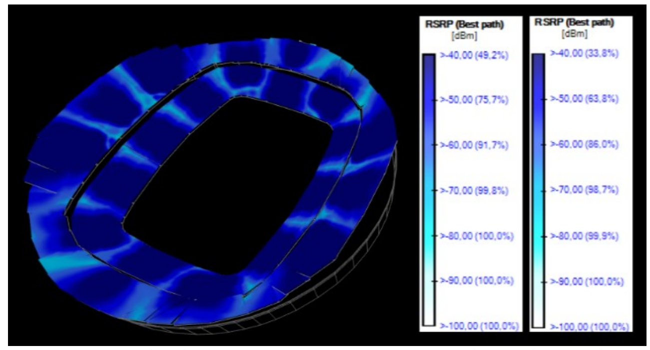

Figure 9 - Final Solution iBwave RSRP output map obtained using the 1800 band.

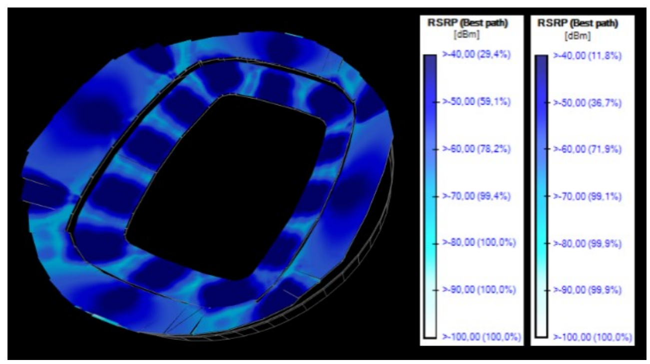

Figure 10 - Final solution iBwave RSRP output map obtained using the 2600 band.

The 2 dB difference in the front-to-back ratio leads to lower SINR values. This degradation can be observed comparing Figure 8 to Figure 11 using 2600 MHz band. This parameter must present high values because this specific rooftop is made of a material that blocks the signal making it impossible for the signal to pass through it and so reflecting the signal to the seating area. The smaller the value, the more unwanted radiation in an undesired direction (back lobe), creating interference in the seats, reflected mostly on the level B corners of the LTE Overlapping Zones output maps.

The average MADR is lower using the 2600 MHz band for all the reasons described, to the values obtained using the 1800 MHz band. For level A, the average MADR was 134.93 Mbps considering the B3 band and 106.98 Mbps using the B7 band. For level B, the average MADR was 131.47 Mbps considering the B3 band and 100.57 Mbps considering the B7 band.

Analyzing the results obtained, the logical next step would be doing another simulation using the final solution configuration but replacing the corner antennas by the CommScope CMAX-DMH60-43-V53 model. With 46 dBm power in other to avoid increasing interference by overlapping sectors.

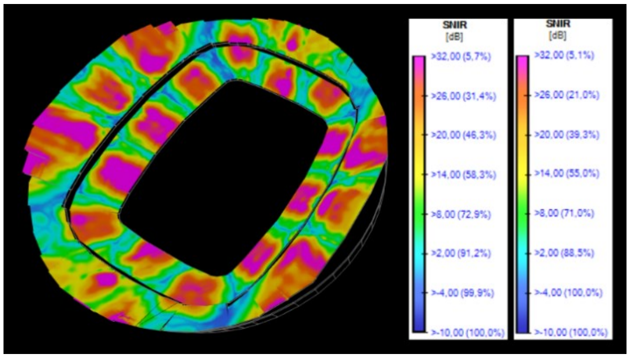

Figure 11 - Final solution iBwave SINR output map considering the 2600 MHz band.

X. CONCLUSIONS

Through a realistic approach, an optimal 4G network solution was studied for the case study stadium. Seeking to provide a good QoE for users in peak situations (game days) and to present the best solution for the maximum time possible, with the use of the minimum equipment.

After doing the site survey, it was possible to conclude that in terms of access for future maintenance and a question of radio efficiency, the antennas need to be placed on the rooftop footbridges. Based on the lower tier shape and the number of seatings per sector coverage area, for the first ring, an almost squared radiation pattern antenna was defined as the best option. However, these allowances were not confirmed for the second ring and so, having in mind that logically each sector should cover more or less the same number of users another antenna model was considered for occupying the positions behind the beacons.

Although it adds complexity to the system, the use of MIMO technique was considered to be essential since it improves the performance and spectral efficiency significantly. However, only a few smartphone models present the capabilities to take full advantage of this type of high MIMO configuration and the associated high modulation schemes. So, the 2x2 was the considered configuration. One of the most critical aspects when designing a network is the distribution of load over the network, so that in peak situations, everyone has the same level of user experience, whether using a more demanding application or not. Since in stadium environments, more specifically in peak situations like half-time, all PRBs are being used it was concluded that the most effective way of doing load balancing is by distributing the number of users equally per each band and not by the band with less PRBs being used.

When comparing all the simulations, the front-to-back ratio appears as one of the most determinant antenna parameters. This is due to the stadium rooftop being made of a material that blocks the signal making it impossible for the signal to pass through it and so reflecting the signal to the seating area, creating interference. So, this parameter should present high values.

As a final remark, it is believed that additional time with a valid license for the iBwave software would provide a more optimized solution. Since a more exhaustive study would result in a more balanced solution between simulations using the 1800 and the 2600 MHz band.

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