# Repositório ISCTE-IUL

# Mobile Communication Systems to Control UAVs: Measurements of QoS Parameters

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*Abstract –* **This paper proposes to identify a propagation model that considers the unmanned aerial vehicles (UAVs) unique characteristics, contemplating two actual wireless technologies, UMTS and LTE, which are theoretically capable of supporting a real-time video service admitting more than one quality index according to the RF conditions. Several measurements were made in a specific outdoor rural scenario in order to understand if the current network infrastructure is prepared to support this type of service using these vehicles, by simulating a real case scenario and considering critical locations where the loss of Quality of Service (QoS) can be significant due to the hole phenomenon that occurs over the antennas/base stations, raising the probability to occur handover.**

*Keywords – Drones, UAV, Mobile communication systems, Measurements of QoS, UMTS, LTE*

## I. INTRODUCTION

THE theoretical research for an empirical propagation model that fits into the unmanned aerial vehicles' (UAVs) unique characteristics was crucial, in order to provide an attenuation estimation based on the transmitted signal, which led to the conclusion that LUI model best suits the unique requirements of these type of vehicles, by assuming unusual heights for the base stations' and terminal's antennas, and a wide frequency interval that permits to include the UMTS and LTE frequency bands [1] [2]. A unique spectrum analyzer was used to understand the variation of certain parameters according to the vehicle's simultaneous changes in a 3D coordinates system (latitude, longitude, and altitude). Parameters like signal strength, interference, and channel capacity/quality were analyzed to understand the viability of the network infrastructure from a specific service provider to accomplish the lowest requisites to transmit a real-time video service using a drone. The measurements were made in three different locations close to two base stations from two distinct service providers, in a rural environment, in order to support empirically the previously referred propagation model. These measurements took in consideration the areas above the base station since it is where it is more common to see a significant drop of signal strength and quality, based on the *hole* phenomenon caused by the lack of coverage from the antennas. The figure 1 demonstrates the proposed flight plan for every measurement done that only considers 10 meters above the base station due to the windy conditions at the time of the trial, that could put at risk the expensive equipment.
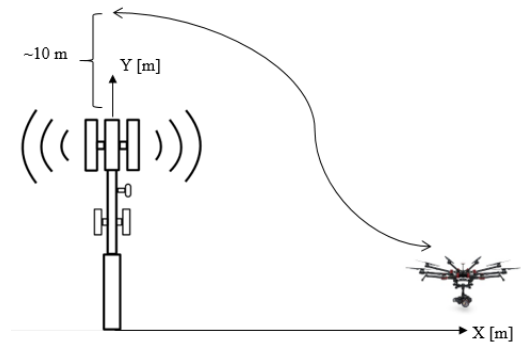


*Figure 1. Proposed flight plan: X (distance to BS) and Y (drone's height) axes*

The samples captured by the spectrum analyzer and its respective parameters were monitored, recorded and saved into a .csv file, using ROMES software provided by Rohde & Schwarz. Afterward, these files were filtered to supply only the necessary information to design 2D and 3D graphics that relate diverse parameters that are essential to understanding whether cellular networks are trustable to support a video streaming service using these unique vehicles in a rural environment.

## II. LUI MODEL

Considering the large quantity of propagation models that exist, it is important to choose one that fulfills the requirements inherent to the UAV's unique characteristics. Firstly, it is necessary to reduce the number of possibilities by defining the type of propagation model: empirical, theoretical or hybrid. In this case, empirical is the best option since it is based in measurements or experimental trials. It is also adequate to identify the environment, scenarios, the base stations' and terminal's station heights, and a frequency range that includes UMTS and LTE frequency bands, ensuring higher data rates to overcome or guarantee the minimum requisites for real-time video. The most known and used empirical models like Okumura, Hata, Cost 231-Hata, Walfish-Ikegami, Erceg and SUI model were developed for specific scenario, assuming a limited frequency range and showing the incapability to consider simultaneously the UMTS and LTE frequency bands. However, LUI model demonstrates the opposite by assuming a wider frequency spectrum from 800 to 2600 MHz. Besides that, most of these models are used in scenarios where the base stations' and terminal stations' height are between 0 and 200 meters and 3 and 10 meters, respectively. These heights are ideal for the

general user equipment like smartphones and notebooks, but it represents a limitation which, once again, LUI model is able to overcome since it considers infinite heights for the base stations and terminal stations. Nonetheless, this model can assume one of two formulas depending on the height of the terminal station, since one of the factors related with the angles of the antenna ($\chi_{angles}$) attenuates significantly the signal strength results when the terminal station's height ($h_{TS}$) is below the base station's height ($h_{BS}$), which is proved by the Graphic-1. However, this factor does not affect that parameter when terminal station's height is above the base station's height, resulting in two distinct formulas to calculate the average path loss in each one of these cases:

$$\begin{cases} L_{[dB]} = L_{0\,[dB]} + 10 \times \gamma \times \log\left(\frac{d}{d_0}\right) \times u(d_{bp} - d) + \\ +\Delta L_{b,f} + [u(h_{TS}) - u(h_{TS} - h_{BS})] \times \Delta L_{bh}\,, h_{TS} < h_{BS} \\ L_{[dB]} = L_{0\,[dB]} + 10 \times \gamma \times \log\left(\frac{d}{d_0}\right) \times u(d_{bp} - d) + \\ +\Delta L_{b,f} + u(h_{TS} - h_{BS}) \times X_{\text{angles}} + \\ +[u(h_{TS}) - u(h_{TS} - h_{BS})] \times \Delta L_{bh}\,, h_{TS} \geq h_{BS} \end{cases} \quad (1)$$

Where $d$ is the distance using a 3D coordination system and can be calculated by using (2).

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \quad (2)$$

$L_0$ represents the free path loss, $\gamma$ stands for path loss exponent and it can assume different values according to the type of environment, $d_0$ is the reference distance, in meters, that vary according to the technology in use which, in this case, assumes picocell characteristics that is represented by $d_0 = 1$ meter. $\Delta L_{b,h}$ is the correction factor associated to the BS effective height and it is usually multiplied by a rectangular function $[u(h_{TS}) - u(h_{TS} - h_{BS})])$ that can result in 0 if: $h_{TS} < 0$ or $h_{TS} > h_{BS}$; or 1 if: $0 < h_{TS} < h_{BS}$. $\gamma$ describes the path loss exponent (3) and it varies according to the terrain category reflected by the parameters a, b and c values, the base station antenna effective height, and the expected result from rectangular and unit step functions $u(h_{TS} - h_{BS})$, where the last function result in 0, if: $h_{TS} < h_{BS}$; or 1, if: $h_{TS} \geq h_{BS}$.

$$\gamma = \left(a - bh_{BS} + \frac{c}{h_{BS}}\right) \times [u(h_{TS}) - u(h_{TS} - h_{BS})] + \vartheta \quad (3)$$

where $\vartheta = 2 \times u(h_{TS} - h_{BS})$. $\chi_{angles}$ is another correction factor that rely on the characteristics of the antennas like azimuth ($\varphi$), elevation angle ($\theta$), tilt of the antenna ($\psi$) and the angle that determines which sector is being used ($\beta$), corresponding to the area from one or more antennas on the base station that provides coverage to the terminal station (4).

$$\chi_{angles} = MIN(\chi_{\theta+\psi}, \chi_{\varphi+\beta}) \quad (4)$$

$\chi_{\theta+\psi}$ is one of the two correction factors necessary to determine the $\chi_{angles}$ result taking into account the elevation and the tilt of the antenna (5).

$$X_{\theta+\Psi} = [1 - \delta(\theta + \Psi)] \times \zeta \quad (5)$$

where,

$$\zeta = [0.0031 \times (\theta + \Psi)^2 - 0{,}6511 \times (\theta + \Psi) - 4.447] \quad (6)$$

Where the elevation angle ($\theta$) can be determined by the formula (7):

$$\theta = tan^{-1}\left(\frac{h_{TS} - h_{BS}}{d(x,y)}\right) \quad (7)$$

$X_{\varphi+\beta}$ is the remaining correction factor to be able to calculate $\chi_{angles}$, that considers the azimuth ($\varphi$) and angle that determines which used is being used ($\beta$), by using the formula (8):
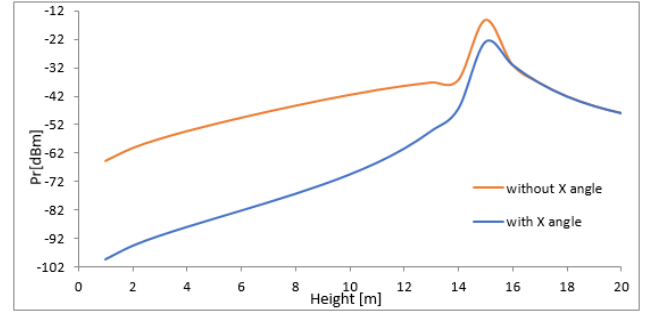
$$X_{\varphi+\beta} = [1 - \delta(\varphi + \beta)] \times (-0.0018) \times (\varphi + \beta)^2 + \Gamma \quad (8)$$

where,

$$\Gamma = -0.0377 \times (\varphi + \beta) + 0.2115 \quad (9)$$

The previous correction factors represented by the formula (6) and (9) use the inverse of the Dirac Delta Function (DDF), which are $(1 - \delta(\theta + \Psi))$ and $(1 - \delta(\varphi + \beta))$. This function can result in 0 or 1, depending on the condition (10):

$$\delta(\theta + (\Psi \vee \beta)) = \begin{cases} 1, & \text{if} \quad \theta + (\Psi \vee \beta) = 0 \\ 0, & \text{if} \quad \theta + (\Psi \vee \beta) \neq 0 \end{cases} \quad (10)$$



*Graphic - 1. Signal strength variation w/ or w/o the $\chi_{angles}$ correction factor, Source: [1]*

## III. EQUIPMENT

Beforehand, it was necessary to take a look at the market to understand which spectrum analyzer would and type of drone would fit in such specific demanding. Firstly, there was the chance to test Spectran HF-60100, that permitted to verify that is capable of determining the signal strength for every individual signal in a certain frequency range defined by the user, using its own software to study the power variations while measuring the signal. However, there are several cons like the autonomy (~20 minutes), limited memory size and the lack of identification from the antennas or base stations unless the directional antenna is pointed exactly to one of them. Based on the previous statements, it wouldn't be possible to obtain sustainable and reliable results. R&S TSME is also a spectrum analyzer able to measure up to eight different technologies simultaneously in the 350 MHz to 4.4 GHz. It is compact, lightweight, low power consumption and it has an internal GPS.



*Figure 2. Spectran HF-60100, Source: [3]*

Unlike the first, it provides information related to base station ID, signal strength/quality, SINR and several codes (MCC and MNC) that permit to identify the service providers. The only defect that affects the final decision is the fact that it needs a full-time physical connection with a host PC, which makes this combination extremely (close to 5 kg, considering the use of a regular laptop) heavy to be lifted by a light/medium caliber drone.

*Figure 3. R&S TSME scanner connected to a laptop, Source: [4]*

Finally, R&S TSMA is similar to TSME but the main and crucial difference between the two is that TSMA is battery powered with rechargeable batteries and charging function, ensuring that is always ready to operate. With its functions, it is possible to analyze and detect radio dead zones (e.g., *hole* phenomenon) or locations with too much interference. It comes with ROMES software that permitted the analysis of the diverse signal related parameters while measuring it and save that progress into a file for future data treatment/filtering. Besides that, it is possible to control the software by establishing a WLAN or Bluetooth connection with a smartphone/laptop/tablet to provide the user interface for configuration before starting the measurement campaign. The only defect is the weight (~2.5 kg) but, in this case, it is possible to overcome it by using a medium/heaving weight drone (e.g. octocopter).



*Figure 4. R&S TSMA scanner and TSMA-BP (battery pack), Source: [5]*

After studying the pros and cons of each spectrum analyzer, it was clear that R&S TSMA was the only able to accomplish the challenges of this measurement campaign, pointing out three characteristics: battery autonomy, lightweight and independence. Furthermore, it was used an octocopter, which is considered to be a medium/heavy caliber drone that was configured to lift 2.5 kg related to the spectrum analyzer together with its battery pack unit and other necessary accessories like Bluetooth/WiFi antennas, cables, etc. In order to attach the equipment to the bottom part of the drone and to also keep it stable during the flight, it was used velcro tape, which it is possible to verify it in the figures 5 and 6.



*Figure 5. Octocopter (drone)*



*Figure 6. Equipment attached below the drone with velcro tape*

## IV. MEASUREMENTS

The main goal in this measurement campaign is to understand how the signals provided by each antenna on the base station behaves during the flight and try to understand if there is any location where the reference sector, which is the sector where the terminal station is located, might not be able to provide sufficient throughput for a video streaming service considering more than one video quality option since the capacity is not the same for UMTS and LTE. If this sector is not able to provide the required quality and strength, the network might consider *handover* if the cellular infrastructure is prepared to support it since these vehicles behaviors are not common when compared to the ones from general equipment. Considering the importance of throughput in video streaming service, it is necessary to verify the recommended bit rates associated to a specific video quality.

*Table 1. Recommended bit rates for video streaming, Source: [6]*

| Video Quality Level | Video (kbps) | Total (kbps) | Comments |
|---|---|---|---|
| VQ1 | 200 | 296 | Smartphone |
| VQ2 | 400 | 496 | Tablet / Smartphone |
| VQ3 | 800 | 896 | Tablet / Smartphone |
| VQ4 | 1400 | 1496 | SD 480P TV screen through games console and STBs, Connected TVs, PCs and Tablets |
| VQ5 | 3150 | 3246 | HD 72P TV screen through games console and STBs, Connected TVs, PCs and tablets |
| VQ6 | 7100 | 7196 | Full HD 1080P, TV screen through games console and STB, Connected TVs, PCs with General Processor Units. |

The video quality parameter varies from 296 kbps (VQ1), which represents the minimum requisites to ensure that video streaming is maintained with the lowest quality, to 7196 kbps (VQ6). However, in this case, the highest quality considered is VQ5 since only PCs and tablets were assumed for supporting the streaming service, so the minimum requirement for highest quality is 3246 kbps according to *Table 1*. Besides the throughput, it was also analyzed the relation between the interference and the signal strength for all the sectors covered by the reference base station.

The measurement results are based in samples captured by the spectrum analyzer for UMTS and LTE technologies, presented by 2D and 3D graphics with the following relations:

- Throughput vs Time
- Throughput vs Signal Strength
- Signal Strength vs Height vs Distance to BS
- Prob. Density Function (PDF) vs Signal Strength/Throughput
- Cumulative Density Function (CDF) vs Signal Strength/Throughput

Based on the fact that all the measurements realized have similar characteristics and goals that are illustrated in *Figure-1*, only one scenario is presented here as a reference to the other two.

- Base Station A:
  - Latitude: 39° 2'23.93"N
  - Longitude: 9°22'30.41"W
  - Service Provider: MEO (MCC: 268; MNC: 06)
  - BS Height: 50 meters
  - Video URL: https://youtu.be/2qXA_rnjnAU
  - LTE channel frequency: 796 MHz
  - UMTS channel frequency: 2152.4 MHz
  - LTE sectors IDs/PCIs:
    - Adjacent sectors: 177/9
    - Reference sector: 178
  - UMTS sectors IDs/PCIs:
    - Adjacent sectors: 34162/4
    - Reference sector: 34163



Figure 7. Base Station A



Figure 8. Scenario B (BS A) and respective flight route

- Departure location: 39° 2'22.77"N; 9°22'31.58"W

- Furthest location from point A: 39° 2'24.30"N; 9°22'30.31"W

- Landing location: 39° 2'22.79"N; 9°22'31.63"W

- BS location: 39° 2'23.93"N; 9°22'30.41"W
The blue dots in the previous figure represent the GPS data samples captured during the flight and the connection between each one of them originates the flight route, which is represented by a white line.

- **LTE** measurement results:
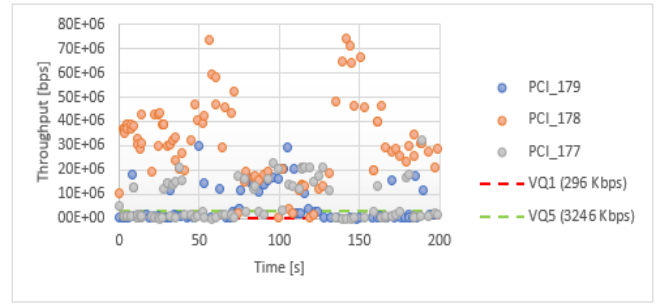


*Graphic - 2.Throughput vs Time considering all sectors from reference BS*
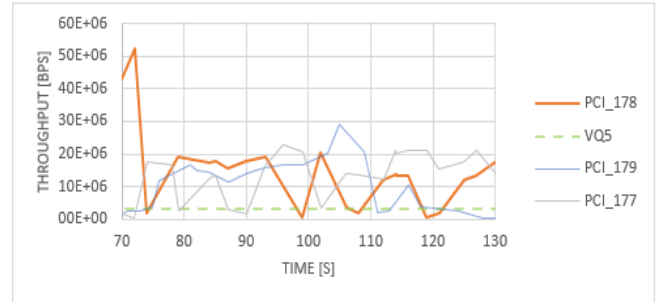


*Graphic - 3. Reference sector results below VQ5 threshold*

*Graphic-2* shows the samples related to the all the sectors covered by the base station A, where it is possible to verify the highest throughput results provided by the reference sector. However, there is a quality regression between 70 and 130 seconds, which is the interval when the terminal station is above the antenna that covers the reference sector, where is not able to fulfill the requirements to sustain a high-quality video streaming. Nonetheless, *Graphic-3* demonstrates that the adjacent sectors from the reference base station are able to compensate the lack of quality to maintain the high demanding for video quality in real-time video service, leading to a *softer handover.* In LTE's case, there is no point in referring the lowest quality (VQ1) due to the fact that any of the presented sectors is able to fulfill the minimum requirements during the entire flight and that is one of the main reasons why the highest quality threshold is considered in this technology. *Graphic-4* illustrates the relation between throughput and signal strength, which leads to the conclusion that they are not directly proportional due to the interference factor used in Shannon's Theorem [7] [8] to calculate the throughput results (11). However, even if in the reference sector looks that way, the adjacent sectors prove it wrong by assuming higher signal strengths than the reference sector in certain locations, but with higher interference that leads to worst quality signals, which is also proved by the order 2 polynomial trendlines for each sector.
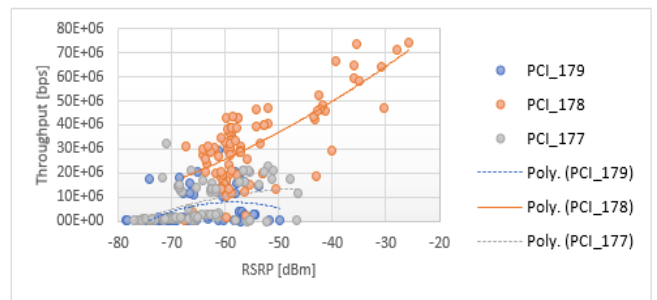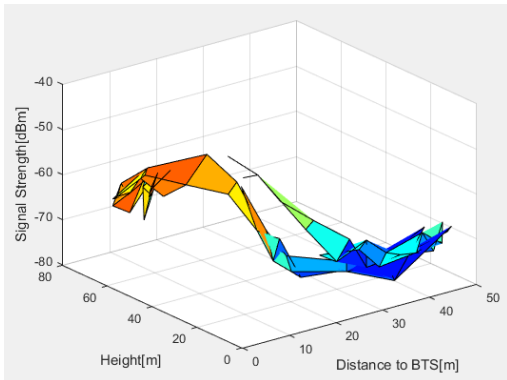


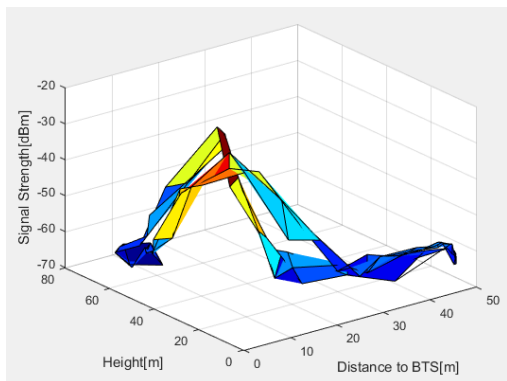*Graphic - 4.Throughput vs RSRP for all sectors from reference BS*

$$C = B \times log_2\left(1 + \frac{S}{N}\right) \qquad (11)$$
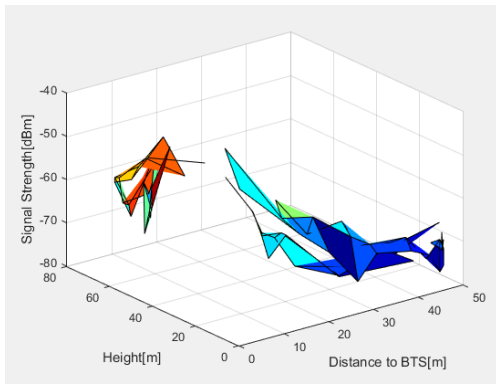
*Graphic - 5. RSRP vs Height vs Distance to BTS for sector 177*



*Graphic - 6. RSRP vs Height vs Distance to BTS for sector 179*



*Graphic - 7. RSRP vs Height vs Distance to BTS for sector 178*

The three previous graphics demonstrate how signal strength behaves according to simultaneously changes in drone's movement like distance to BS and its height from the ground level. The *Graphics-5/6* are related to the adjacent sectors of the base station A, demonstrating that the spectrum analyzer wasn't receiving any signal strength from the antennas covering the adjacent sectors when close to 40 meters height, which corresponds to the antennas' height in base station A.

Unlike the previous cases, the reference sector results that are illustrated in Graphic-7, demonstrate that, close to the same location, it is capable of providing greater signal strength results due to the fact that terminal station (drone) is located in front of the main lobe of the antenna covering the present sector.
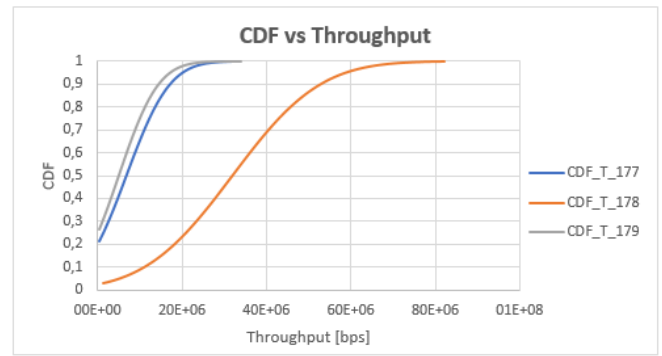


*Graphic 8. CDF vs Throughput; LTE: 796 MHz; Sc: B*

The *Graphic-8* exhibits the probability of each sector reach a certain signal strength/throughput value. In this case, the reference sector represented by the orange line is predominant, assuming the highest probability to reach higher results in both parameters when comparing to the remaining sectors from the same base station. The adjacent sectors assume almost the same probabilities. However, the sector represented by the blue line (CI: 177) has a higher probability to assume superior results when compared to the ones from the remaining sector (CI:179), but this difference is not significant. In this scenario, the spectrum analyzer did not capture any information about sectors from adjacent base stations using the same channel frequency, considering this technology and the same service provider.

- **UMTS** measurement results (2152.4 MHz):
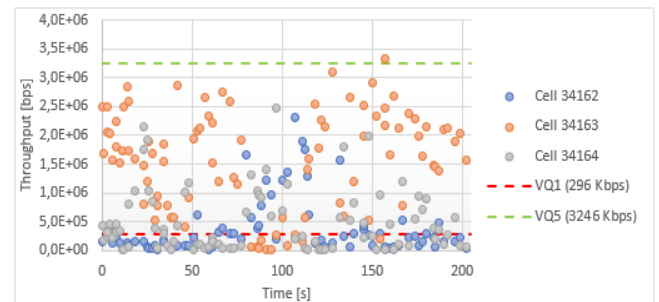


*Graphic - 9. Throughput vs Time for all sectors from the reference BS*
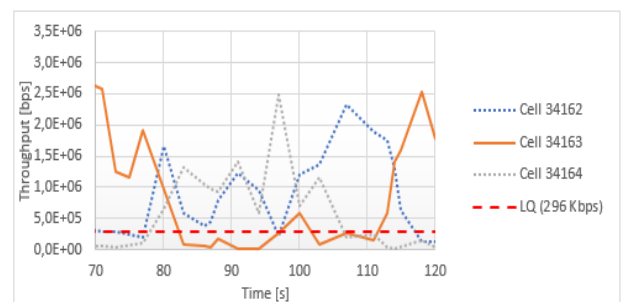


*Graphic - 8. Reference sector throughput below poorest quality*

In UMTS, lower throughput results are expected according to the theoretical limits related to this technology and this is illustrated in *Graphic-9*, where only one sample from the reference sector is above the highest quality threshold. Based on the previous statement, it is expected that the main goal for UMTS is to guarantee the minimum requisites to support a real-time video due to its limitations. However, the reference sector does not provide enough throughput during the entire flight and that is demonstrated in the interval from 70 to 120 seconds described in Graphic-10 but, once again, the adjacent

sectors from the same base station are able to provide enough capacity to guarantee the minimum requisites to maintain a video streaming service, even if in the lowest quality, assuming the existence of a softer handover event in these cases.
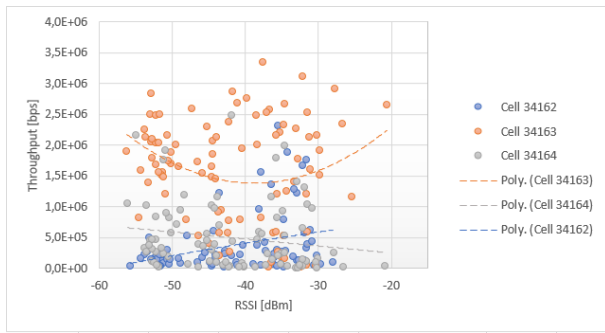


*Graphic - 9. Order 2 polynomial trendlines for every cell in reference BS*

The trendlines expressions relating the signal strength and throughput represented in Graphic-11 have some similarities to the ones from LTE but, in this case, the one corresponding to the reference sector does not assume such a constant growth. However, in the remaining sectors, they are similar.
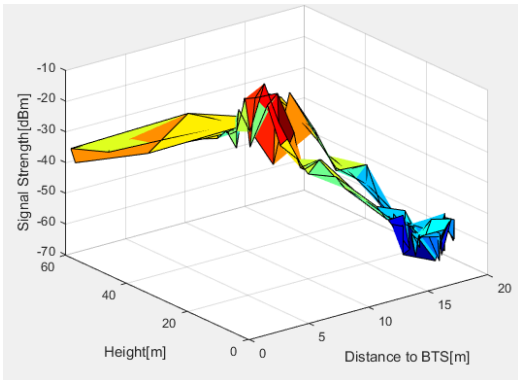


*Graphic - 10. RSSI vs Height vs Distance to BTS for sector 34162*
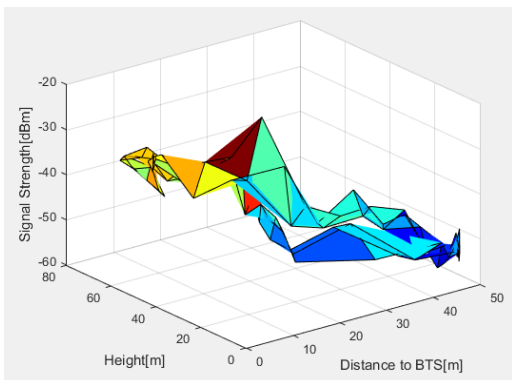


*Graphic - 11. RSSI vs Height vs Distance to BTS for sector 34164*
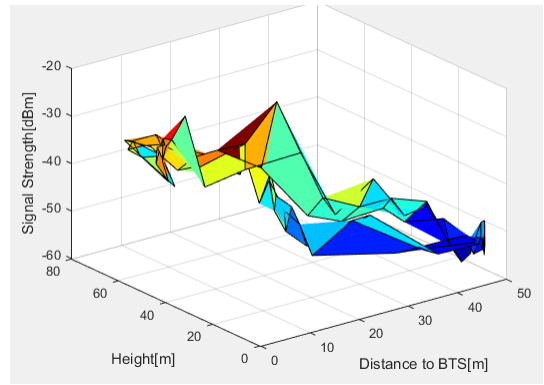


*Graphic - 12. RSSI vs Height vs Distance to BTS for sector 34163*

The *Graphics-12/13/14* relate the signal strength parameter from UMTS technology (RSSI) with the simultaneous changes in drone's distance to the BS and its height. One of the adjacent sectors (CI: 34162) is only able to capture the first sample when 20 meters distance away from the BS, while the others capture it in the beginning of the measurement when close to 50 meters distance. However, any of these sectors provide RSSI values greater than -60 dBm, which is considered as a high signal according to the table 2 and proves that even when acquiring these RF conditions, its quality differs substantially due to the interference and it is more noticeable in this technology like it was possible to evaluate by the relation between the *Graphics-15/16*.

*Table 2. RSSI limits for GSM/3G(UMTS)/HSPA, Source: [9]*

| RSSI Interval | RF Conditions |
|---|---|
| [-50 to -75] [dBm] | High signal |
| [-76 to -90] [dBm] | Medium signal |
| [-91 to -100] [dBm] | Low signal |
| [-101 to -120] [dBm] | Poor signal |

Based on the Graphic-16, it is possible to conclude that any sector belonging to the base station A has almost the same probability of reaching a certain signal strength value. However, the probability to achieve a certain throughput value differs significantly from the reference sector to the other sectors, which proves that even with the same RSSI results, the interference has a great impact and it is a decisive factor to understand if a determined channel has enough capacity/quality to support a determined service according to the Shannon's Theorem formula.
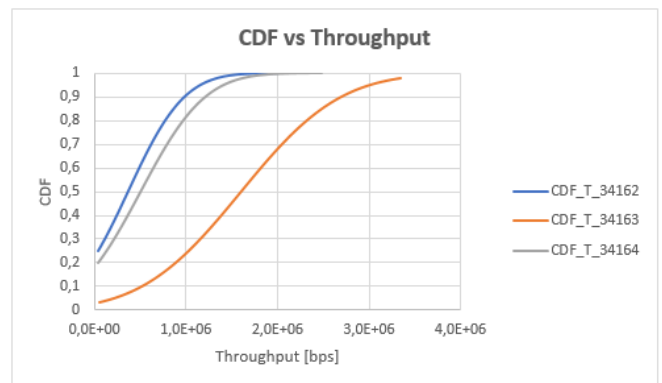


*Graphic - 13. CDF vs Throughput; UMTS: 2152.4 MHz; Sc: B*

Based on the Graphic-15, it is possible to conclude that any sector belonging to the base station A has almost the same probability of reaching a certain signal strength value.

However, the probability to achieve a certain throughput value differs significantly from the reference sector to the other sectors, which proves that even with the same RSSI results, the interference has a great impact and it is a decisive factor to understand if a determined channel has enough capacity/quality to support a determined service according to the Shannon's Theorem formula. Comparing the PDF graphs from both technologies, it is possible to verify that it is harder to rely on RSSI results due to the fact that the three sectors from this BS get close values, while in LTE, where RSRP is the parameter used for signal strength, the difference of these values from sector to sector is more noticeable. In this scenario, the spectrum analyzer did not capture any information about sectors from adjacent base stations using the same channel frequency, considering this technology and the same service provider.

## V. CONCLUSIONS AND FUTURE WORK

The antenna supporting the reference sector is able to fulfill the minimum requisites when using LTE since there are no samples below the minimum video quality threshold (VQ1), which corresponds to 296 kbps. However, by using this technology, the demand must be greater to achieve the highest quality (3246 kbps), in order to support a higher resolution in more than one type of device. To be able to achieve such quality, it is not trustable to rely only on the reference sector due to the fact that it can't keep higher data rates during the entire flight but it is possible when considering *softer handover* where the adjacent sectors from the same base station provide better quality signal when comparing to the reference sector in certain moments of time during the flight.

As expected, UMTS is not able to achieve such higher rates when compared to LTE. However, the demand is not as high as in LTE and the main goal is to maintain or overcome the minimum requisites for video streaming during the entire flight, by providing a throughput equal or above 296 kbps using the reference sector or adjacent sectors. Based on this technology measurement results, in the interval of time where the *hole* phenomenon takes place, the reference sector is not able to achieve the minimum requisites but the adjacent sectors from the same base station are able to compensate it if *softer handover* is taken into account, Based on this technology measurement results, in the interval of time where the hole phenomenon takes place, the reference sector is not able to achieve the minimum requisites but the adjacent sectors from the same base station are able to compensate it if softer handover is taken into consideration and the video broadcasting might stop while this event occurs. The hole phenomenon occurs at the top of the base station/antennas in both technologies. However, if the main goal is to guarantee the minimum service requisites, the reference sectors achieve it using LTE technology. When considering UMTS, it was only possible to accomplish it from the beginning until the end of the flight if softer handover event occurs. So, if LTE technology is available, it is more reliable to use it under these circumstances. Nonetheless, the interference effect over the signal leads to the premise that high signal strength does not mean a high-quality signal and this is more noticeable in UMTS where all the sectors get almost undistinguished probabilities to assume the same values according to the results. However, the throughput values are distinct from sector to sector because it takes into account the interference effect over the signal, which is the most important factor to understand if the network is able to support a determined service. It would be interesting to perform new measurement

campaigns in diverse environments (urban, suburban and rural) considering the same flight plan but flying the drone until the maximum height permitted by the legislation. According to the Portuguese law, it is possible to fly a drone to a limit of 120 meters height when in user's line of sight. Besides that, assuming a new flight plan where the drone would have to go from one BS to another from the same service provider, by also assuming the highest possible altitude according to the legislation and verify if the infrastructure is ready to guarantee the Quality of Service (QoS) for the same or other services that require higher data rates.

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