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BARCELONATECH

Doppler shift compensation strategies for LEO satellite communication systems

A Degree Thesis

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by

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Abstract (English)

Broadband connectivity only covers one third of the earth's surface. LEO satellite communication systems can be a solution to extend and complement terrestrial networks. Nevertheless, mobile ground-terminals receive high Doppler shift over the satellite channel, due the relative motion between the satellite and the mobile terminal. In this project is analysed the Doppler shift over the satellite channel observed by a mobile terminal. The analysis is done implementing a Matlab Orbital simulator transmitting an OFDM signal. Also is proposed a Doppler shift compensation strategy for LEO communications systems with the implementation of an ML Doppler estimator in the OFDM receiver. Several results are presented to evaluate the Doppler observed by the terminals in different positions as well as the BER for different SNR and Doppler shift.

Resumen (Castellano)

La conectividad de banda ancha actualmente sólo cubre un tercio de la superficie terrestre, los sistemas de comunicación por satélite LEO pueden ser una solución a tener en cuenta para ampliar y complementar las redes terrestres. Sin embargo, los terminales terrestres móviles reciben un cambio elevado de la frecuencia (efecto Doppler) sobre el canal satélite debido a las velocidades de movimiento relativas entre el satélite y el terminal móvil. En este proyecto se estudia el efecto Doppler sobre el canal satélite observado por un terminal móvil. El análisis se hace implementando un simulador Orbital Matlab que transmite una señal OFDM. También se propone una estrategia de compensación Doppler para los sistemas de comunicaciones LEO con la implementación de un estimador Doppler ML en el receptor OFDM. Se presentan varios resultados en términos de Doppler observado por los terminales en diferentes posiciones, así como la BER para diferentes SNR y Doppler recibido por los terminales.

Resum (Català)

La connectivitat de banda ampla actualment només cobreix un terç de la superfície terrestre. Els sistemes de comunicació per satèl·lit LEO poden ser una solució a tenir en compte per ampliar i complementar les xarxes terrestres. No obstant això, els terminals terrestres mòbils reben un canvi elevat de la freqüència sobre el canal satèl·lit a causa de les velocitats de moviment relatives entre el satèl·lit i el terminal mòbil. En aquest projecte s'analitza el efecte Doppler sobre el canal satèl·lit observat per un terminal mòbil. L'anàlisi es fa implementant un simulador Orbital Matlab que transmet un senyal OFDM. També es proposa una estratègia de compensació Doppler per als sistemes de comunicacions LEO amb la implementació d'un estimador Doppler ML en el receptor OFDM. Es presenten diversos resultats en termes de Doppler observat per els terminals en diferents posicions, així com la BER per a diferents SNR i Doppler rebut per els terminals.

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Glossary

A list of all acronyms and the meaning they stand for.

LEO: Low Earth Orbit

GEO:Geosynchronous Equatorial Orbit

SNR: Signal to Noise Ratio

BER: Bit Error Rate

LoS: Line of Sight

NLoS: No Line of Sight

ML: Maximum Likelihood

OFDM: Orthogonal Frequency Division Multiplexing

LTE: Long Term Evolution

Cp: Cyclic Prefix

GPS: Global Positioning System

1. Introduction

This project was conceived from the observation that there is broadband connectivity only in one third of the earth's surface. Underdeveloped countries, remote rural areas and most of the maritime zones do not have access to 4G communications. The main reason is because the population density of the aforementioned areas is not sufficiently high to ensure profitability when deploying and operating networks infrastructures. Current solutions to provide connectivity in remote areas are based on satellite communications, but they don’t allow smartphones to directly connect to the satellite constellation. This observation has led to the exploration of an alternative solution to the traditional path, which is based on the possibility of creating a satellite constellation that offers access network to handheld terminals. The idea is illustrated in Figure 1. This would have a high cost at the beginning (due to the cost of making the satellites) but in the long term it would be more efficient and less costly to deploy than conventional networks. It is worth emphasizing that the integration of satellite networks in 5G is in the roadmap of 3GPP [1]

GEO (geostationary orbit) satellite deployments orbit at an altitude of 35786 Km and are characterized by a slow motion around its orbital position with respect to a point on the Earth. Compared to terrestrial cellular systems, communication networks based on GEO satellite have a large propagation delay that has to be taken into account in the overall design of the satellite network and high propagation losses. By contrast, Low Earth Orbit (LEO) satellites orbit at an altitude of 300-3000 km. As a consequence, they are characterized by a lower propagation delay, lower propagation losses and a higher Doppler shift than GEO satellites. This fact justifies the need for transmitter-receiver architectures that are robust to Doppler effects when LEO satellite deployments are considered.

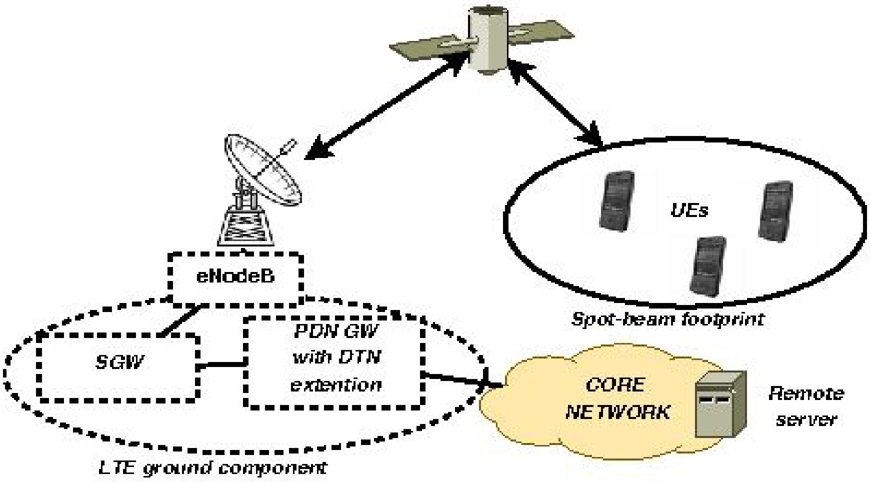

Figure 1: LEO communication system scheme

In satellite systems the received signal strength is one of the most critical aspects. In GEO satellites the propagation losses are very high, due the long distance between the satellite and the terminal. However, in LEO satellites systems the propagation losses are smaller which facilitates that smartphones may establish connection with the satellite. Furthermore, the lower delay in LEO satellite systems compared with GEO systems is another aspect that tips the balance towards LEO.

The main problem that was analysed within this idea was that signal suffers from the Doppler shift, due to the relative motion between the satellite and the terminal. Therefore, the project is concentrated on solving this problem. Being able to characterize the Doppler effect with the visible time of the satellite has allowed to resolve the problem of the Doppler shift in LEO communication satellite systems to a high extent, which is crucial to complement and extend the terrestrial networks

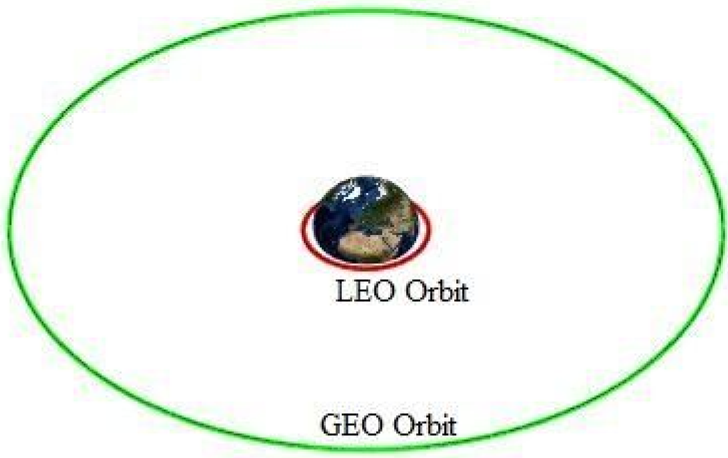

Figure 2: LEO and GEO orbit

There are certain requirements and specifications needed to obtain the results presented in this project. The mathematical software Matlab was essential because all the procedures were done using this program. Certain specifications were made in Matlab in order to produce the LEO parameters and therefore create an accurate and real simulation for the process to develop. There are two main aspects to the creation of this environment: the delimitation of orbit between 300 km and 3000 km in height and the restriction of inheriting the OFDM modulation format from the terrestrial standards, such as LTE.

This project is built upon other works related to satellite networks that investigate the Doppler effect. In this sense, Irfan Ali's paper, "Doppler Characterization for LEO Satellites" explains how Doppler shift changes with the maximum elevation angle and allowed the characterization of the Doppler effect in any orbit. The second part of, "Guidelines for evaluation of radio transmission technologies for IMT-2000" describes the channel models that are used in the project. The paper "ML Estimation of Time and Frequency offset in OFDM systems" by Jan-Jaap Van de Beek which defines the estimator of the Doppler shift, is used in this project for the estimation at the receiver. Lastly, the "CubeSatToolbox" in the Matlab software by Princeton Satellite Systems has permitted to create the satellite orbits where the simulations were created.

The main contribution of this project is:

- Analysis of the Doppler shift for different maximum elevation angles between the terminal and the satellite.
- Implementation with Matlab software an orbital simulator able to calculate the satellite position and velocity in function of time.
- Characterization of the satellite channel model
- Define a method to compensate the Doppler shift
- Analysis of the degradation of the OFDM signal
- Analysis of the compensated Doppler shift in different points off the cell
- Implementation of a ML Doppler shift estimator
- Study of the BER in different points of the cell, altitude of the satellite orbit, radius of the cell and elevation angles.
- Study the limits of the ML Doppler shift estimator

1.1 Gantt Diagram

1.2 Work plan

Create OFDM Signal:

- In this section the OFDM scheme (transmitter and receiver) has been implemented with Matlab.

Create orbital model:

- Adapt the orbital simulation CubesatToolbox of Princeton Satellite Systems to the desired conditions.

Characterize Doppler Shift:

- Implement the Doppler shift characterization into the Matlab orbital simulator
- Define a method to compensate the Doppler shift
- Analysis of the Doppler shift for different altitude of orbits and radius of the cell
- Analyse the worst point of the cell
- Analyse the behaviour of the Doppler shift
- Analysis of the BER of an OFDM signal in the implemented conditions

Characterization of the channel:

- Implement and analyse the satellite channel model

Define possible solutions:

- Implementat an ML Doppler shift estimation in the OFDM receiver
- Integrate the Matlab orbital model, the OFDM signal and the Doppler simulations in a unique simulation
- Analyse the BER with the ML Doppler estimator in different points of the cell
- Analyse the Doppler estimation
- Analyse the BER in function of the radius of the cell
- Analyse the BER in function of the SNR

1.3 Description of the incidences that may have occurred

Time simulation: Maltab simulations took a lot of time to run, due the simulation that calculates at every second: the position of the satellite, the Doppler shift in different points of the Earth and some other parameters. When it’s simulated a single transmission and reception of an OFDM signal in these conditions it takes a while, but when it is required to simulate several trials to have more relevant data for the BER (bit error rate) it take a lot of time, in the order of several hours.

2. Theoretical Background and scenario characterization

This section provides a brief introduction of the main concepts that have been analyzed in this project and the characterization of the scenario under study.

2.1 Doppler Shift

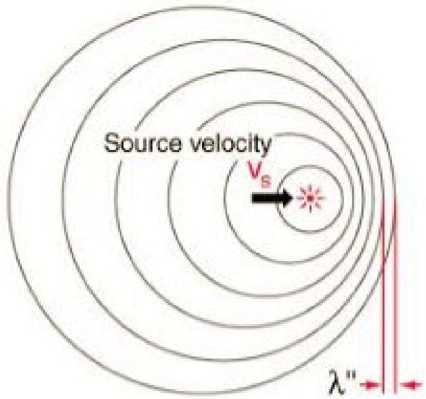

Figure 3: Doppler effect

The Doppler shift is observed when a source of waves is moving in relation to an observer or vice versa. This movement produces a change in frequency in relation to observer.

Without loss of generality, we will focus on the case where the source is approaching the destination. In such case, the phenomenon is produced when the transmitter of the waves is approaching the observer, each successive wave is emitted from a closer position than the previous wave. For that reason, the time between the arrival of successive wave fronts is reduced and the wavelength decreases. Therefore, the frequency increases. By contrast, if the source is moving away, the distance between successive wave fronts grows in wavelength. In this case, the frequency decreases. Nevertheless this frequency change is not a result of an alteration from the source.

When the speed of the source and the speed of the receiver are much lower than the propagation velocity of the waves, the observed frequency can be expressed as:

$$f = \left(1 + \frac{\Delta v}{c}\right) f_0 \tag{1}$$

where: $\Delta v = v_r - v_s$ is the relative motion between the satellite and the terminal, therefore *vr* is the velocity of the receiver and *vs* is the velocity of the source. The propagation velocity in this case is the speed of the light $3 \cdot 10^8$m/s, which is denoted as *c* and finally *f0* is the carrier frequency emitted by the source.

This change in frequency can be expressed as:

$$\Delta f = \frac{\Delta v}{c} f_0 \tag{2}$$

where the Doppler shift is defined as the difference of frequencies between the received frequency and the emitted frequency by the source, that is $\Delta f = f - f_0$.

2.2 Orbital assumptions

In this project the Low Earth Orbits are analyzed in order to characterize the channel and the Doppler effect that a terminal will suffer. The trajectory of the satellite is made with Matlab software creating an Orbital satellite simulation. For that reason, this section explains the principal characteristics of these type of orbits and the equations used to create the Matlab simulator.

Low Earth Orbits are in the range between 300km to 3000km of altitude and are characterized for the orbital velocity needed to maintain the satellite in orbit, which is about 7.8km/s in the lowest orbits. As the orbital altitude increases, the velocity is reduced. Due this high velocity, the orbital period is about 100 minutes, consequently the visibility window duration in one point of the Earth is very short. Owing to the low altitude of the orbits, the satellites suffer the atmospheric drag provoked by the gasses of the upper layers of the atmosphere in consequence the velocity of the satellite is reduced and the satellite losses height. This atmospheric drag produces that the angular velocity of the satellite fluctuate over the course of time. In addition, in the Earth centered fixed (ECF) coordinate system the satellite's velocity varies with the latitude due the Earth rotation. During the visible time, the orbit of the satellite can be approximated by a circle arc. In addition, the variation of the angular velocity of the satellite in the ECF frames during the visibility window is less than 0.3% for LEO circular orbits. Hence, it can be concluded that the angular velocity can be approximated by a constant:

$$\omega_F \approx \omega_s - \omega_E cos(i) \qquad (3)$$

where ω_s is the angular velocity of the satellite, ω_E is the angular velocity of the Earth (2*pi/(24*3600) and i is the inclination of the orbit.

In this project, the Doppler shift is analysed for a terminal located in Barcelona (Coordinates: 41.4ºN 2.2ºE) in different orbit altitudes from 500km to 2500km.

Minimum elevation angle to archive connection between the terminal and the satellite is considered minimum elevation angle for visibility θ_v =10º.

The simulation of the dynamics of the satellite is done by a Fourth order Runge–Kutta method [2]. This method is used to approximate the solutions of differential equations in the discrete-time domain.

The dynamics of the satellite are simulated using the CubeSatToolbox [3]. The vector that contains the dynamics of the satellite is defined as x=[r,v,q,w] where r is the position vector of the satellite, v is the velocity vector of the satellite, q is the quaternion of the spacecraft and w is the angular velocity of each axis of the satellite. Quaternions is a four dimension vector that contains the orientation and rotation angles of the three axis of the satellite, which is used to parametrize the attitude of the satellite.

In the Matlab simulator implemented, the dynamics are calculated every second (h=1s) of the orbit for all the duration range that is defined in the beginning of the simulation.

The dynamics of the satellite in the discrete-time instant t_n are described as x_n, however, the dynamics after a time step of h=1 second x_{n+1} can be computed as:

$$x_{n+1} = x_n + \frac{1}{6}(k_1 + 2(K_2 + k_3) + k_4) \tag{4}$$

where the coefficients k_1, k_2, k_3 and k_4 are defined as:

$$\begin{aligned} k_1 &= f(t_n, x_n) \\ k_2 &= f(t_n + \tfrac{h}{2}, x_n + k_1\tfrac{h}{2}) \\ k_3 &= f(t_n + \tfrac{h}{2}, x_n + k_2\tfrac{h}{2}) \\ k_4 &= f(t_n + h, x_n + k_3 h) \end{aligned} \tag{5}$$

k_1 is the increment at the beginning of the interval. k_2 and k_3 are the increment at the midpoint of the interval. Finally k_4 is the increment based on the slope at the end of the interval.

The Matlab function that the Runge-Kutta method evaluate is the Righ-Hand-Side function. This Matlab function uses an atmospheric model to calculate the atmospheric drag and other disturbances that the satellite surfers.

The output of this function is the derivative of the x vector in the instant t_n:

$$xDot = \frac{\partial x}{\partial t} \tag{6}$$

The resulting vector can be expressed as:

$$xDot = [v; vDot; qDot; wDot] \tag{7}$$

where the derivative of the position is the velocity vector v of the satellite in the instant t_n. VDot, qDot and wDot are the derivation of the velocity, quaternion and angular velocity of each axis. Using this method the dynamics of the satellite are computed.

2.3 Doppler Equation for LEO Satellites

The information of the characterization of the Doppler shift has been taken from Irfan Ali papper "*Doppler characterization for LEO Satellites*" [3]

For LEO satellite communication systems, the Doppler frequency at terminals varies with time. This time the varying phenomenon is caused by the line of sight component of the relative velocity vector, evolving from the rapid movement of the satellite in its orbit, in relation to the ground transceiver, which includes satellite velocity and the relative velocity due the Earth's rotation. This can be characterized by the maximum elevation angle from the terminal to the satellite during the visible time. More specifically, the Doppler shift is zero when the satellites are in the maximum elevation angle and at its closest position to the terminal; on the other hand, at a lower elevation angles this shift is larger. These calculations are specifically done only for the amount of time that the satellite becomes visible to the terminal.

The normalized Doppler Shift can be computed as the derivative of the distance vector between the satellite and the mobile terminal s(t) divided by the propagation velocity of the waves:

$$\frac{\triangle f}{f} = \frac{-1}{c}\frac{\partial s(t)}{\partial t} \tag{8}$$

The coordinate system is an Earth centred fixed coordinate system.

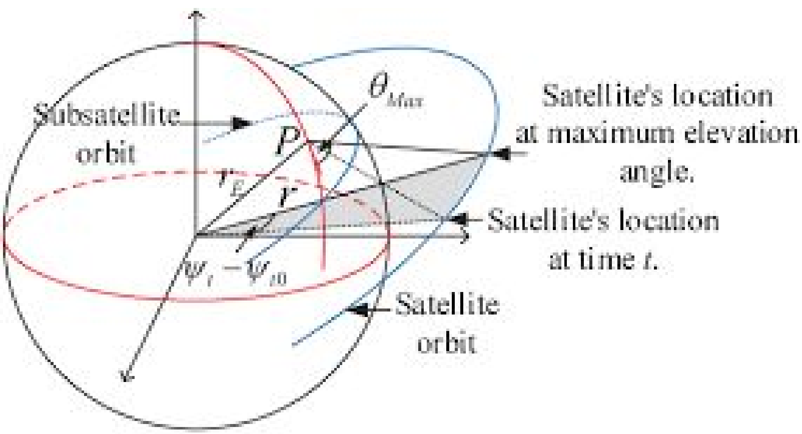

Figure 4: Satellite geometry

The coordinates where the mobile terminal is located it's denoted as P, therefore θ_{max} the maximum elevation angle during the visibility window. The distance between the center of the Earth and the satellite *r* can be described as the sum of the radius of the Earth r_E plus thet altitude of the orbit ***h*.**

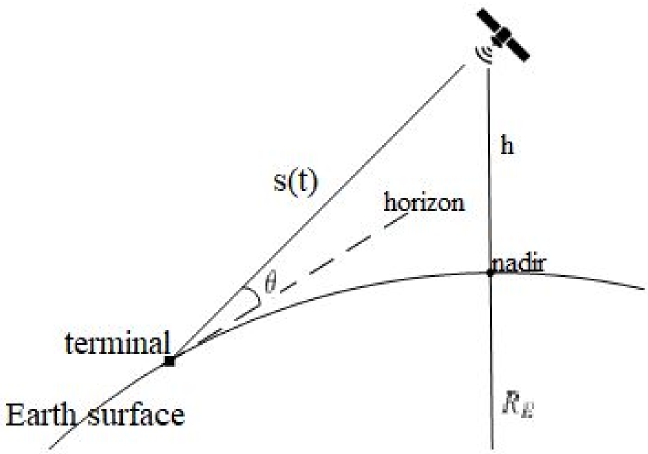

Figure 5: Elevation angle between the terminal and the satellite

Applying trigonometry to the triangle plane of the satellite position (Figure 6), allows to obtain the equation of the range vector between the satellite and the terminal s(t), as follows

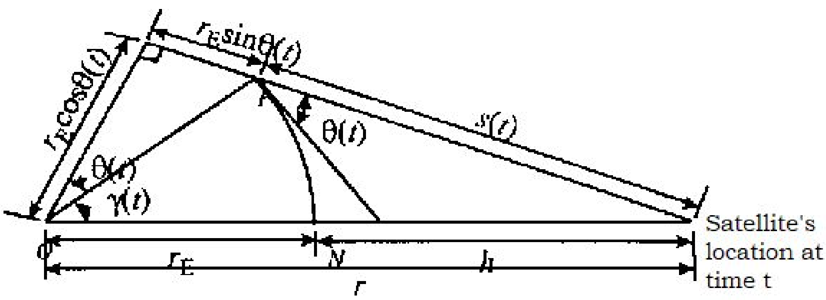

Figure 6: Satellite triangle plane

$$s(t) = \sqrt{r_E^2 + r^2 - 2r_E r cos\gamma(t)} \tag{9}$$

The angle γ is defined as the angle between the vector defined from the center of the Earth to the satellite position and the vector that goes from the center of the Earth to the mobile terminal position.

The instant when the terminal reaches the maximum elevation angle, is denoted as t_0. In addition, the fact that the maximum elevation angle can be expressed as:

$\theta(t_0) = \theta_{max}$, allows the equation to be satisfied,

$$cos(\theta_{max} + \gamma(t_0)) = \frac{r_E}{r} cos\theta_{max} \qquad (10)$$

Moreover, the angular distance measured on the surface of earth along the round trace between the maximum elevation angle point and the instantaneous point is $\psi(t) - \psi(t_0)$ as seen in equation (11).

$$cos\gamma(t) = cos(\psi(t) - \psi(t_0))cos\gamma(t_0) \qquad (11)$$

The normalized Doppler shift is the derivative of the vetor s(t) divided by the speed of the light as it's explained in (8).

Therefore, differentiating the equation of the slang range (equation (9)) the result will remain in function of the calculated in the $cos\gamma(t)$equation (11). So, substituting the equation (11) in the derivative of s(t) we obtain the next expression:

$$\dot{s}(t) = \frac{r_E r sin(\psi(t) - \psi(t_0))cos\gamma(t_0) \cdot \dot{\psi}(t)}{\sqrt{r_E^2 + r^2 - 2r_E r cos(\psi(t) - \psi(t_0))cos\gamma(t_0)}} \qquad (12)$$

The angular velocity of the satellite in the ECF fame can be expressed as:

$$\omega_F(t) = \psi(t) \qquad (13)$$

Substituting expression (10), (12) and (13) in equation Doppler (8). We obtain the closed-form expression of the Doppler as function of the elevation angle.

$$\frac{\triangle f}{f} = -\frac{1}{c} \frac{r_E r \sin(\psi(t) - \psi(t_0)) \cos(\cos^{-1}(\frac{r_E}{r} \cos(\theta_{max}) - \theta_{max}) \cdot \omega_F(t)}{\sqrt{r_E^2 + r^2 - 2r_E r \cos(\psi(t) - \psi(t_0)) \cos(\cos^{-1}(\frac{r_E}{r} \cos(\theta_{max}) - \theta_{max})}} \qquad (14)$$

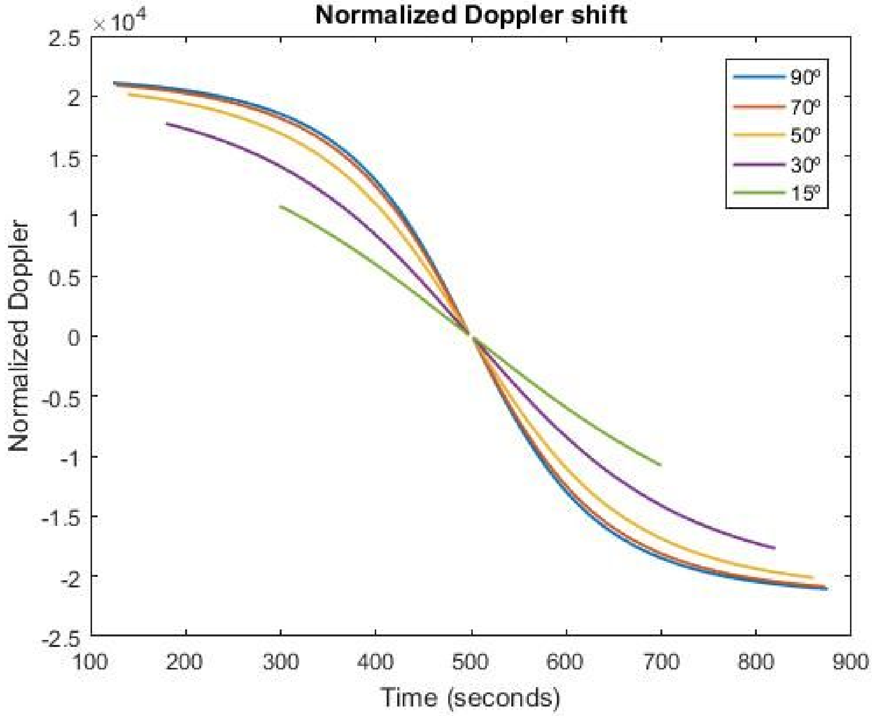

Figure 7: Doppler-time S-curve for maxim elevation angles

In Figure 7 is represented the Normalized Doppler shift (the relation between the received frequency and the emitted frequency) for maximum elevation angles of: 90º(Blue), 70º(Red), 50º(Yellow), 30º(Purple) and 15º(Green). The conditions of the orbit in this case are an altitude of 1000km, for a mobile terminal situated in Barcelona how it's specificatied in 2.2 section and an inclination orbit of 98º.

2.4 Visibility Window Duration

The visibility window is the time when the terminal has direct visibility with the satellite. We have assumed that the minimum elevation angle to achieve connectivity is 10 degrees.

The visibility window can be defined as:

$$\tau(\theta_{max}) = 2\left|t_v - t_0\right| \tag{15}$$

Where t_v is defined the instant when the satellite just becomes visible to the terminal. In this particular instant the satellite will be in the minimum elevation angle for visibility θ_v .

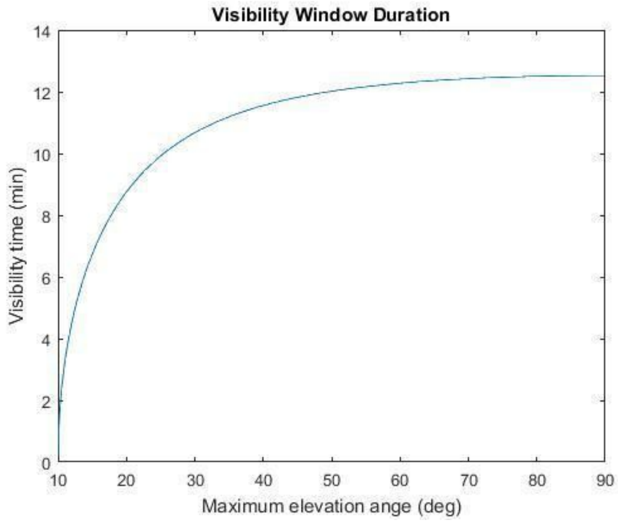

Figure 8: Satellite visibility window duration

The visibility window duration can be expressed as:

$$\tau(\theta_{max}) \approx \frac{2}{\omega_s - \omega_E cos(i)} cos^{-1}\left(\frac{cos(cos^{-1}(\frac{r_E}{r}cos\theta_v) - \theta_v)}{cos(cos^{-1}(\frac{r_E}{r}cos\theta_{max}) - \theta_{max})}\right) \quad (16)$$

Figure 8 shows the duration of the visibility time for a LEO orbit of 1000km altitude in function of the maximum elevation angle, it has a logarithmic behaviour. Also, the maximum visibility window duration is less than a 14 minutes.

2.5 Doppler in LTE standard

The applicability of LTE in a satellite scenario is limited by the impact of the satellite channel impairments on its requirements and procedures. In particular, specific attention must be paid to the Doppler shift.

The LTE standard contemplates that the maximum Doppler shift that a terminal can experiment is that of a high speed train. In this scenario, the maximum speed is less than 500 km per hour and the carrier's frequency is 2Ghz. The maximum Doppler shift results in 950Hz. In the satellite communication, the Doppler shift will be much larger with the maximum Doppler considered in LTE specifications. In a satellite system, the Doppler shift would be larger than that of LTE. In the considered scenario with a carrier frequency of 2GHz, the Doppler shift would be within the range of: -45KHz<=fd<=45kHz.

That would make that the communication can't be established between the mobile terminal and the satellite.

2.6 OFDM signal

Orthogonal frequency division multiplexing (OFDM), is a communication technique that divide a transmission bandwidth, into a number of closely evenly-spaced frequency bands. In each one is transmitted one sub-carrier that transports a portion of the information. Each subcarrier is orthogonal to the rest, giving it the name to this multiplexing technique by frequency division. OFDM is a very flexible and efficient modulation technique used in many wireless standard like: LTE, LTE-Advanced, WiMAX, Digital Audio and Video Broadcast, WLAN, and ADSL.

The main advantage of OFDM is its ability to provide robustness against frequency selective fading, because it divides the overall channel into multiple narrowband signals that can be modelled as flat fading sub-channels.

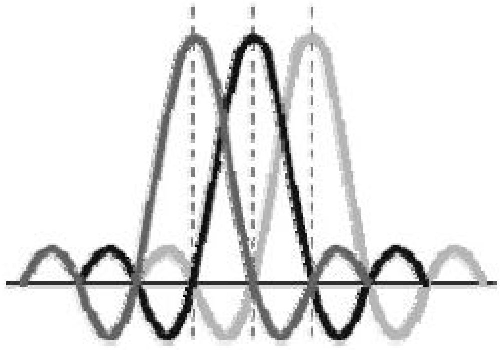

Figure 9: OFDM frequency spectrum

The most important advantages of OFDM are: Resilient to ISI (inter-symbol interface) due the Cyclic prefix that introduces a guard interval between symbols, resilience to interface due the signal is divided in sub-carriers, if one carrier frequency is interfered only is loss a portion of the transmitted signal and simple channel equalization due the signal is transmitted in many narrowbands signals rather than one fast wideband signal.

The fact that each subcarrier is orthogonal to the rest allows that the spectrum of each subcarrier be overlapped and there is no interference, increasing the efficiency from the better use of the spectrum.

An OFDM system takes a flow of modulated data (QAM, QPSK,..) and divides it into N parallel flows, that's the serial to parallel block function. Then each flow is mapped to a subcarrier and combined using the inverse fast Fourier transform (IFFT) obtaining the signal in the time domain to be transmitted. In this moment, the cyclic prefix is added to the signal. This is an important characteristic of the OFDM signal and is based on repeating a small part of the information. This cyclic prefix provides a guard interval between symbols to eliminate intersymbol interference and simplifies the channel estimation and equalization. In these project, the cyclic prefix is also exploited to estimate the Doppler shift and the delay of a symbol.

After adding the cyclic prefix, the signal is converted to serial and it's transmitted through the channel. The length of this prefix should be equal or higher than the channel impulse response.

The receiver is basically a reversed version of the transmitter. First of all, the signal is converted serial to parallel. Then, the cyclic prefix is removed. Next, the information conveyed on each subcarrier can be extracted by applying the Fast Fourier Transform (FFT). After that, the signal is converted in a serial data flux.

In the matrix form, the received signal after the FFT can be expressed as:

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{w} \tag{17}$$

where s is the vector of symbols, w the noise vector and **H** is the channel matrix that has the channel frequency response on the main diagonal. On the *k*th subcarrier, the received signal can be expressed as

$$r[k] = H[k]s[k] + w[k] \tag{18}$$

where H(k),s(k) and w(k) denote the channel frequency response on the received subcarrier, the transmitted symbol and the additive noise.

Figure 10 shows an OFDM scheme explained in this section

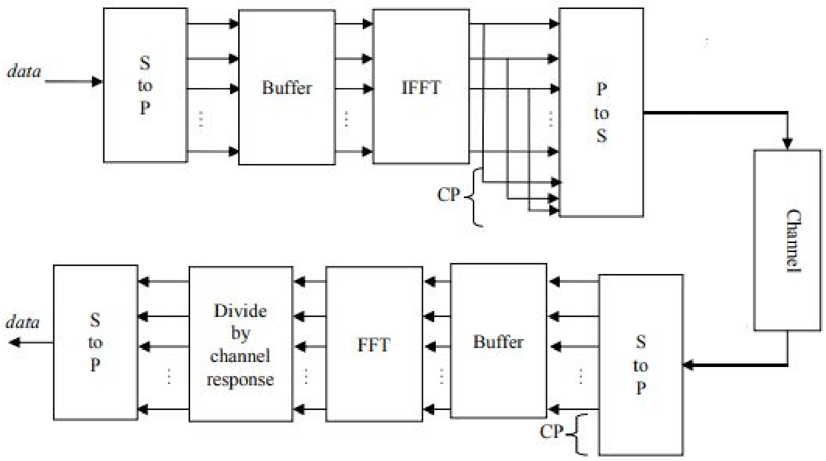

Figure 10: OFDM Scheme

2.7 Satellite Channel model

To make more realistic simulation, the channel where the OFDM signal propagates have to be implemented in the Matlab code. In this section, the channel model for a satellite communications is explained. The channel can be characterized in two parts, one part is due to the scattering and the obstacles around the terminal and the other one is the deterioration of the signal due the Doppler shift.

The satellite propagation model use a line of sight (LoS) component with a Rice distribution and a multipath component (NLoS) with Rayleigh distribution due the reflections of the signal. The delay between these taps are in the order of nanoseconds. Also the LOS component have a power level much larger than the NLoS taps.

The ITU proposed three types of channels, in this project is implemented the most restrictive channel that represent the 90% of the delay spread values.

Tap Number	Relative tap delay values (ns)	Tap amplitude distribution	Average amplitude with respect to free space propagation
1	0	LOS:Rice NLoS: Rayleigh	0 dB -12.1dB
2	60	Rayleigh	-17.0dB
-3	100	Rayleigh	-18.3dB
4	130	Rayleigh	-19.1dB
5	250	Rayleigh	-22.1dB

Table 1: Channel Model

Finally the channel impulse response can be express as:

$$h(t,\tau) = (\sqrt{P_{LoS}} + h_0(t))\delta(t) + \sum_{l=1}^{L-1} h_l(t)\delta(\tau - \tau_l) \qquad (19)$$

Now we are going to add the second part of the channel provoked by the Doppler shift.

The transmitter signals spread in different multipath components that each one experiment a Doppler shift and a propagation delay. In the previous section it's explained the delay and power of this multipath components. Now we are going to analyze the Doppler change for each one.

As it is explained in the section 2.4, the Doppler shift is a change of the frequency of the signal. This means that in the temporal domain will cause a phase rotation that depends on the severity of the Doppler effect. That is:

$$\rho(t) = exp\left(j2\pi \int_0^t f_d(t')\delta t' + j\theta_0\right) \tag{20}$$

The Doppler shift is assumed to be constant during the symbol time. Then, the carrier frequency offset can be expressed as:

$$\rho(t) = exp(j2\pi f_d t + j\theta_0) \tag{21}$$

Denoting the transmitted signal as s(t), the channel impulse response as h(t), the phase rotation as p(t) and n(t) as the additive, then it follows that the received signal at the input of the receiver can be expressed as:

$$r(t) = exp\left(j2\pi f d t + j\theta_0\right) \int_{-\infty}^{\infty} h(t,\tau) s(t-\tau)\delta\tau + n(t) \tag{22}$$

By sampling the received analog signal, we can express the received signal in the discrete-domain as:

$$r[k] \approx exp\left(j2\pi \sum_{i=1}^{k} fd(iTs)Ts + j\theta_0\right)\left(\left(\sqrt{P_{LoS}} + h_0[k]\right)s[k] + \sum_{l=1}^{L-1} h_l[k]s[k-k_l]\right) + n[k] \tag{23}$$

where Ts is the sampling period and r[k]=r(kTs).

3. Doppler shift compensation strategies

In this section the strategy to combat the negative impact of the Doppler effects is described.

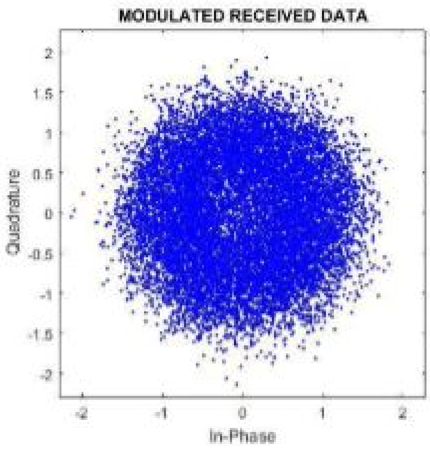

Figure 11: Modulated received data

The high Doppler shift doesn't allow 4G communication systems such as LTE to be implemented in LEO satellite systems. The Doppler is approximately 50 times bigger than that tolerated in LTE receivers. That's the reason why a Doppler compensation methods have to be applied.

I proposed two methods to compensate the Doppler shift. The first one is to compensate all the Doppler at the mobile terminals, while the second one is that the satellite compensate most part of the Doppler shift and the terminal compensate the residual part of it.

1rst Method: Doppler Shift compensation at the terminal.

In this method the mobile terminal knows the position of the satellite and its own position. Hence, it has to know the orbit of the satellite to compute the Doppler shift that will be experienced. With these method any terminal can receive the signal in any position of the Earth. However, the method has some big disadvantages. One of the biggest problems stems from the limited computational capacity of the terminals. To compensate the Doppler, the terminal needs to calculate the orbit of the satellite and the Doppler shift that the terminal will suffer at each instant. In addition, the way that the terminal has access to the position of the satellite is not a trivial task and seems difficult to obtain.

2nd Method: Doppler Shift compensation at the satellite.

This method consist in defining a static ground cell, where the satellite will provide coverage. In this method the satellite has to know the position of the center of the cell and its own position.

With the GPS system it's really easy to obtain the coordinates, due the GPS constellation have an attitude orbit of 20180km much higher than the LEO. Based on this information, the satellite only has to compensate the Doppler shift that a user located at center of the cell will experience.

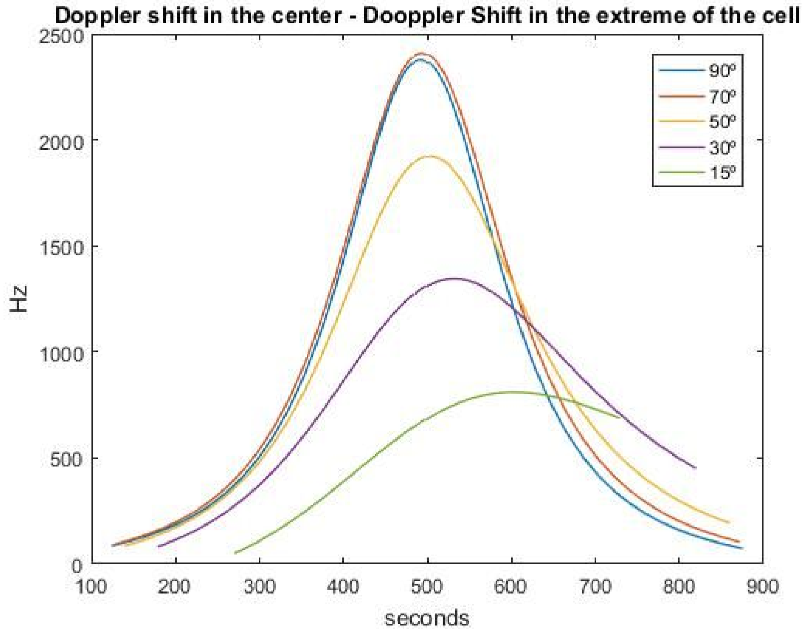

Figure 12: Doppler shift observed in the extreme of the cell after compensation in the center

The ground position doesn't change and these simplify the calculations that the satellite have to do. Applying this method, the terminals in the center of the cell or in the very near positions will receive a negligible Doppler shift. Moreover, terminals that are inside of the cell will suffers a reduced Doppler shift, when compared to the case where no compensation is done. Now the residual Doppler shift depends on the position of the user in the ground cell. In Figure 12 is represented the Doppler that a mobile terminal will receive in the edge of the cell. For a cell of 100km radius the maximum difference of Doppler between the center and the worst extreme of the cell is 5KHz. Without any compensation, the Doppler shift will be increased by a factor of 10. The bigger is the cell, the higher is the residual Doppler experienced by edge users. It becomes evident that the residual Doppler increases with the cell size.

The method used in these project to reduce the Doppler shift is the second one for many reasons:

- The principal reason is the computational calculations the terminal have to do, in the chosen method the terminal only has to estimate the residual Doppler, which can be done by existing methods exploiting the OFDM modulation format. Nevertheless, in the other method the terminal has to calculate the Doppler shift received during the visibility window duration.
- The second reason is the occupation of the traffic channels. In the first method the terminal has to receive the information about the parameters of the orbit from other satellite or terrestrial base station. This data will load the traffic channel with control information. But in the chosen method this problem doesn't exist.

4. ML Doppler shift estimator

Applying the Doppler compensation in the center of the cell explained in the previous section, the Doppler shift in the edges of the cell it's still very high. The terminal receiver can't demodulate the signal. In the following figure we can observe the OFDM transmitted data, and the modulated received data in the case of a cell of 100km and in the case of a cell of 50km of radius. The BER in both case is of a 50%, that means that the received data is completely loss.

LTE Parameters	
Length Cyclic Prefix	16
Sample Frequency	15.36MHz
Symbols	14
Subcarrier spacing	15kHz

Table 2: LTE parameters used

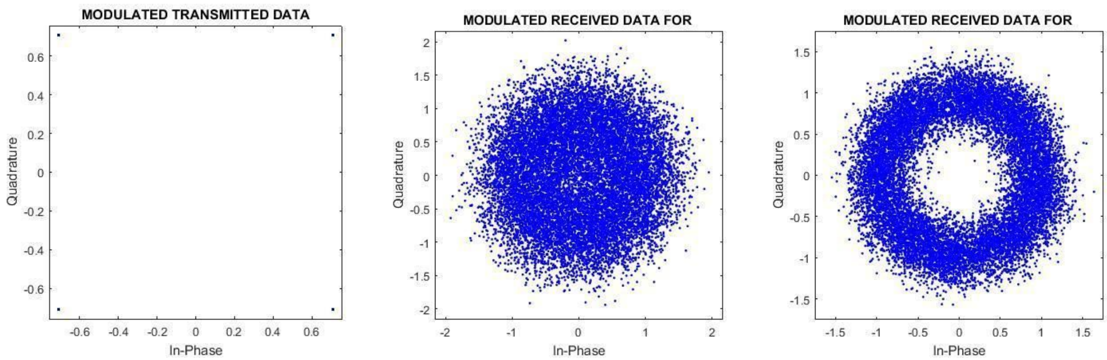

Figure 13: (a) (b) (c)

(a)Transmitted modulated data, (b) Received data for 100km radius cell, (c) Received data for 50km radius cell

In Figure 14 is represented the gradient of the Doppler shift. This graphic represents the variation in Hz of residual Doppler shift in each second. The maximum variation for a f_0=1GHz in one second is 15Hz. This maximum variation is produced during the transition time to the maximum Doppler shift. When the Doppler is maximum, the variation of it is 0. Due this variation of 15Hz in a second, the variation during the transmission of an OFDM symbol of 1024 samples is negligible, because the sampling frequency is 15,36MHz.Therfore, in the duration of one OFDM symbol the Doppler shift can be considered constant in the transmission time.

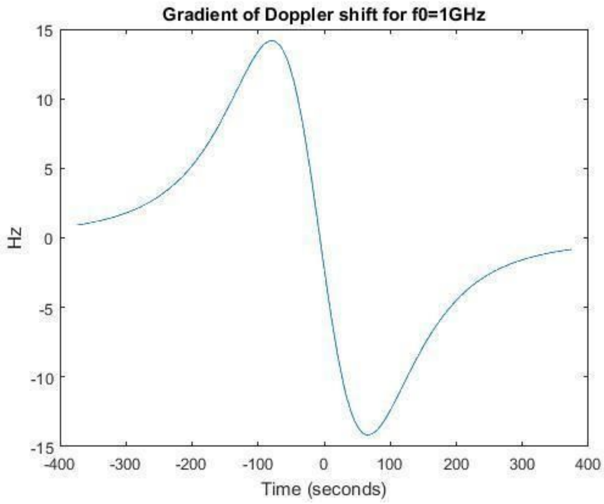

Figure 14: Gradient of the Doppler shift

The method to recuperate the signal that is proposed in this project, is to include a ML Doppler shift estimator in the OFDM receiver to compensate this residual Doppler shift. The Doppler estimation proposed is the ML estimator proposed by Jaan-Jaap van de beek and Magnus Sadell [4].

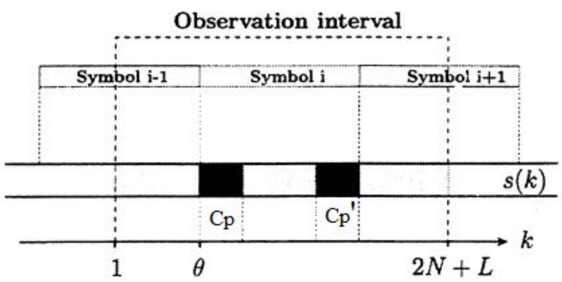

Figure 15: Observation interval scheme of the received data

As it's explained in the OFDM section, thanks to the cyclic prefix we can obtain the symbol timing and the estimation of the Doppler shift.

Suppose that we observe 2N+L samples of the received signal r(k) described in 2.7 section and these samples contain one complete OFDM symbol of (N+L) samples, where N is the length of the OFDM block and L is the length of the cyclic prefix. The beginning of the symbol within the observed block of samples is unknown due the channel delay where θ is the integer-valued unknown arrival time of a symbol. The samples that contain the cyclic prefix Cp are the copy of the of the L final samples of the OFDM symbol. For that reason the samples in the cyclic prefix Cp and their copy are correlated while the remaining samples r(k) are mutually uncorrelated. Taking advantage of this property, the delay θ and the carrier frequency offset (Doppler Shift) ε can be estimated.

Using the correlation properties of 2N+L consecutive samples, the log-likelihood function is used to estimate the variables. After several derivation steps, the ML estimation of θ and ε is the argument maximizing Λ.

$$\Lambda(\theta,\varepsilon) = log\ f(\mathbf{r}|\theta,\varepsilon) = |\gamma(\theta)|\, cos(2\pi\varepsilon + \angle\gamma(\theta)) - \rho\Phi(\theta) \qquad (24)$$

where:

$$\gamma(m) = \sum_{k=m}^{m+L-1} r(k)r^*(k+N) \qquad (25)$$

is the sum of L consecutive correlations between pairs of samples spaced N samples and

$$\Phi(m) = \frac{1}{2}\sum_{k=m}^{m+L-1} |r(k)|^2 + |r(k+N)|^2 \qquad (26)$$

is the energy term independent of the frequency offset ε. Also the contribution of Φ in the log-likelihood expression Λ depends of the weighting factor

$$\rho = \frac{SNR}{SNR+1} \qquad (27)$$

Maximizing the log-likelihood function the two variables can be estimated as

$$\hat{\theta}_{ML} = arg\ max_m \left\{|\gamma(m)| - \rho\Phi(\theta)\right\} \qquad (28)$$

$$\hat{\varepsilon}_{ML} = -\frac{1}{2\pi}\angle\gamma(\hat{\theta}_{ML}) \qquad (29)$$

Now the carrier frequency offset can be estimated by an easy way and also an important parameter that is the delay of the signal to synchronize the transmitter and the receiver.

The performance of this ML estimator is shown in the results section.

Once the Doppler shift is estimated, the OFDM receiver has to counteract this disturbance. As it is explained in the section 2.6 the received signal in an OFDM system after A/D conversion can be expressed as:

$$r\left[k\right] = exp\left[j\left(2\pi\sum_{p=1}^{k} f_{Doppler}(p)T_s\right)\right] s\left[k\right] * h[k] + n[k] \tag{30}$$

Where h[k] is the chanel model and n[k] is the additive noise. The normalized time-varying Doppler shift can be defined as:

$$\varepsilon = f_{Doppler}(p) \cdot T_s \tag{31}$$

Now the function of the received signal can be rewritten as:

$$r\left[k\right] = exp\left[j\left(2\pi\sum_{p=1}^{k}\varepsilon\right)\right] s\left[k\right] * h[k] + n[k] \tag{32}$$

This is the OFDM signal in the receiver, before convert the data serial to parallel the signal goes through the ML estimator were its obtained the $\hat{\varepsilon}_{ML}$.

To counteract the Doppler shift with the estimated variables only have to multiplying the received signal by the exponential of the above expression but with the sign inverted.

$$r_{ML}\left[k\right] = r[k]exp\left[-j\left(2\pi\hat{\varepsilon}_{ML} \cdot k\right)\right] \tag{33}$$

Using this method, the Doppler shift can be successfully compensated in most of the cases. In the section 5 is analysed the performance and the limits of this method.

5. Results

In this section is shown the numerical results of the project.

5.1 Doppler shift in different points of the cell

Applying the Doppler compensation in the center of the cell we will analyze the positions where will receive high Doppler shift. The frequency offset that the terminal receive with this method is the Doppler shift in the center of the cell if the satellite emits at a constant f_0 minus the Doppler shift received in the position of the terminal.

If the terminal is exactly in the center of the cell, the Doppler shift received will be 0, but if the terminal is in the extreme of the cell, the Doppler shift will be much higher. Now we are going to analyze in which point of the cell the terminal will receive the highest residual Doppler shift.

There are four points of interest in the extremes: the two parallel points to the trajectory of the satellite, which are shown in blue in the Figure 16, and the two perpendicular points to the orbit of the satellite, which correspond to the green points in the Figure 16.

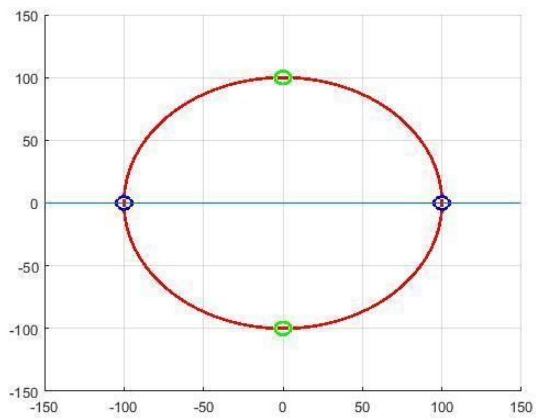

Figure 16: Analyzed points of the cell and satellite ground track(blue) for θ_{max} =90º

As it's explained in Section 2.3, the Doppler shift changes with the elevation angle between the terminal and the satellite. In the points parallel to the orbit, the elevation angle is the same seen at the center but at different time instants. This produces that the residual Doppler shift is quite big due the difference of elevation angles. Analyzing the two parallel points, the elevation angle observed in these points is very similar to the elevation angle in the center of the cell. For that reason the residual Doppler shift is much smaller.

In the Figure 17 we can observe the maximum Doppler shift perceived in each point of the cell. As we can see the Doppler shift change in the direction of the orbit of the satellite, also the Doppler shift in the perpendicular direction is quite constant.

The worst two points are the extremes of the cell which the satellite passes over in the first time and the last time.

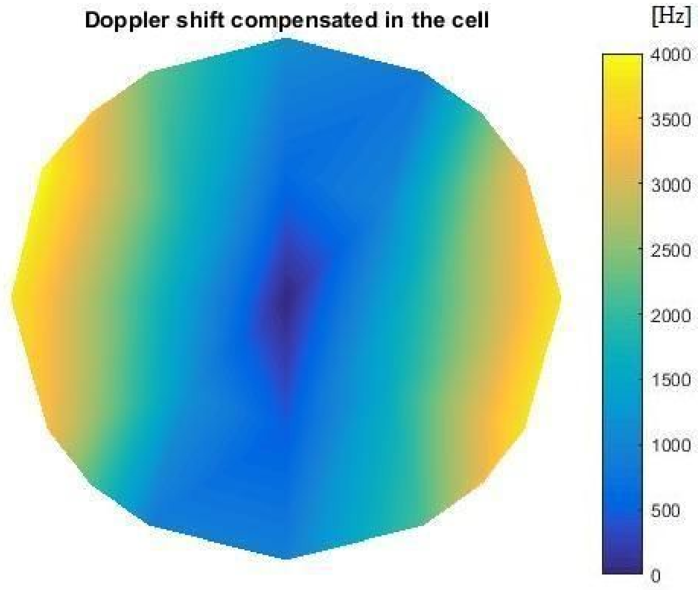

Figure 17: Residual Doppler shift observed in the cell

Now the maximum Doppler shift in one of the two worst places of the cell is analysed with different cell radius.

The Figure 18 represents the Doppler shift that the terminal will receive in the worst position of the cell after the compensation with the Doppler shift in the centre of the cell.

The graphic evolves as it is expected. The larger is the radius of the cell, the larger is the difference of elevation angles that the terminal will see in the extreme of the cell. Hence, the elevation angle with the centre of the cell will increase. Also we can interpret this graphic as the Doppler shift received in a position parallel to the orbit trajectory in function of the distance between the position and the centre of the cell.

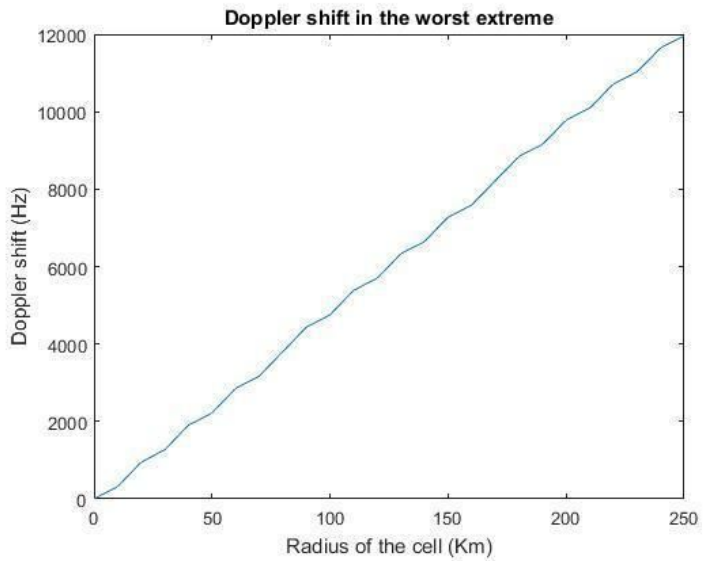

Figure 18: Doppler shift observed in the extreme of the cell in function of the radius of the cell

5.2 Doppler shift as function of the height of the orbit

In this section is analysed the difference of Doppler shift between the Doppler received in the centre and the Doppler shift received in the worst extreme of the cell as function of the height of the orbit.

In Figure 19, we can observe that the residual Doppler is reduced as the height of the orbit increases. The calculations are made for a cell of 100km of radius.

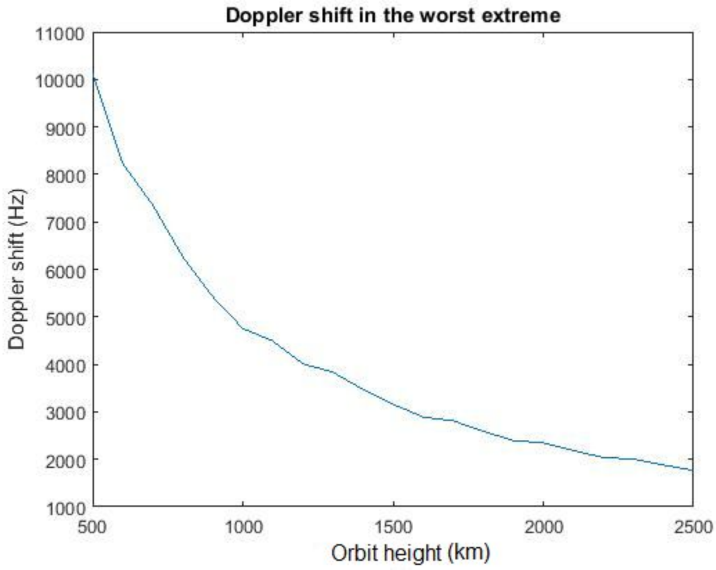

Figure 19: Residual Doppler in the extreme in function of the height of the orbit

This effect is due to the change in the elevation angle. For low orbits the elevation angles that the terminal in the worst extreme will see and the elevation angle in the centre of the cell is very different. By contrast, in height orbits, the elevation angle seen by the both positions are more similar and this reduces the Doppler shift after the compensation.

5.3 Estimation of the Doppler shift

In section 4 is explained how to estimate the Doppler shift that the terminal will receive and in this section we will analyse how correctly the ML estimator can estimate the Doppler shift.

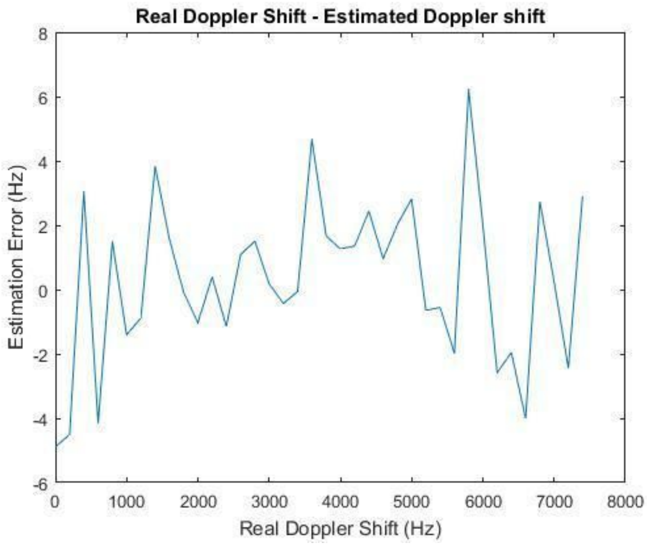

Figure 20: Error of the estimated Doppler

In the previous figure it's represented the difference between the real Doppler shift that the terminal will receive and the estimated Doppler shift that the ML estimator calculates.

As the figure highlights, the difference between the real and the estimated Doppler is pretty low considering that the Doppler received in the terminal is very high. The maximum difference is 6Hz, taking into account that the LTE standard can tolerate 950Hz of Doppler shift we can consider that's a good Doppler estimator under the conditions described in the project.

5.4 ML Doppler shift estimator

As we see in the Sections 4 and 5.1, although the Doppler shift is compensated in the centre, the Doppler shift component in the extremes of the cell it's still large. The signal received can't be demodulated. Only if the radius of the cell it's small enough, the Doppler shift is less than the 950 Hz that the LTE standard can tolerate. But the objective of this project is to provide coverage to the maximum terrain extension possible. That's the reason why it's implemented an ML Doppler shift estimator to counteract the residual Doppler shift remaining of the centre compensation and being able to increase the radius of the cell. In this section the performance of the ML Doppler shift will be analysed.

In Figure 21 the BER is represented for different SNR with the channel model explained in section 2.7. In blue is represented the BER after the centre compensation, in red the BER with the implementation of the ML estimator and finally the yellow line represents the Bit Error Rate for 0 Doppler shift.

The Doppler effect degrades the BER compared with the ideal one of 0 Doppler shift.

The orbital conditions taken into account for the analysis of the BER are: orbital height of 1000km, radius of the cell 100km, a mobile terminal situated in Barcelona, maximum elevation angle of 90º, f_0 of 1GHz, QPSK symbols and subcarrier spacing of 15kHz.

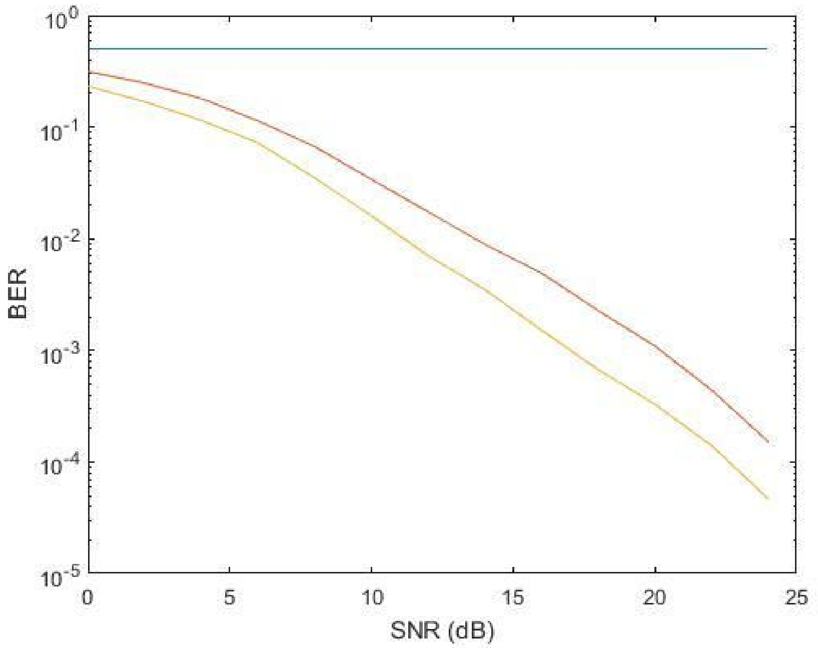

Figure 21: BER in function of the SNR

The BER follows the expected behaviour. At low SNR the AWGN noise and the model channel deteriorates the signal and that's the reason why the BER are considerable, differently the SNR is large the noise doesn't affect the signal and the bit error rate is practically 0. The BER curve with the implementations of the ML estimation approaches to the ideal with zero Doppler shift.

The following figures show the signal received without the ML estimator for SNR of: 5dB, 10dB, 15dB and 20 dB with a cell radius of 100Km and f_0=2GHz. The receiver perceive a Doppler shift of 4.5 KHz in these conditions thus, the signal is completely distorted and lost.

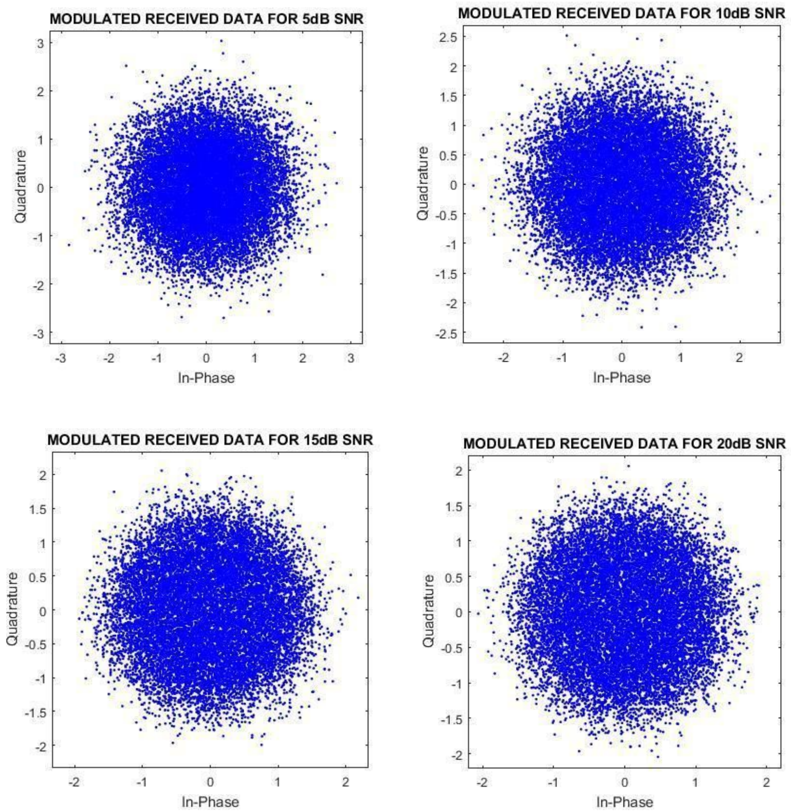

Figure 22: Received modulated data without ML estimator

Implementing the ML estimator explained in the section 4, the Doppler shift that suffers the signal can be estimated and counteract this in the OFDM receiver. The following Figure 23 shows the modulated received data after correct the Doppler shift with the ML estimator.

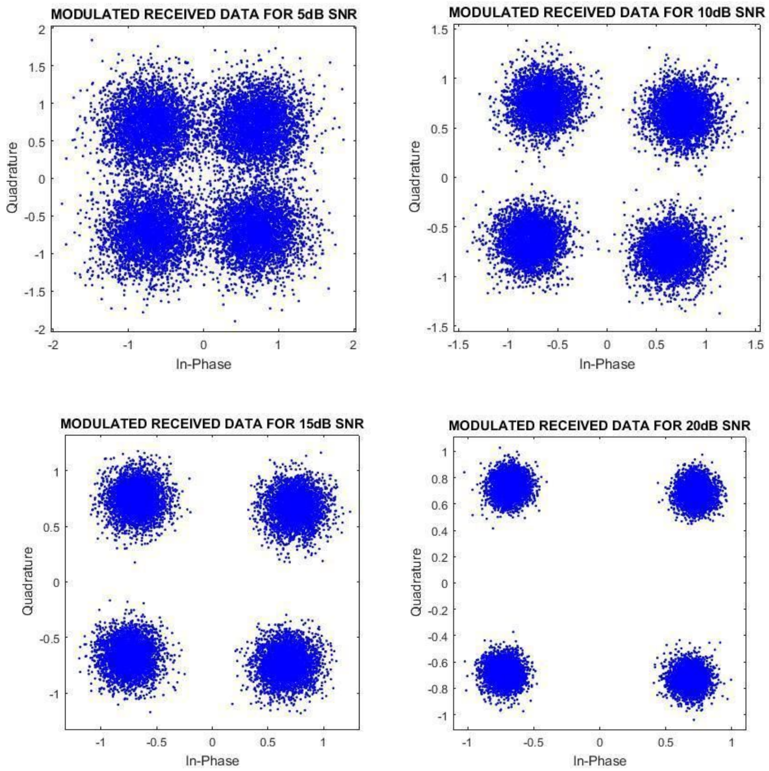

Figure 23: Modulated received data after the ML estimator

How can it be observed, with the ML Doppler shift estimator, the modulated received data can be recovered.

5.5 ML Doppler shift estimator Limit

In this section is analysed the maximum Doppler shift that the ML Doppler shift estimator can tolerate. If the ML estimator starts to fail form a Doppler frequency, this would delimit the maximum radius of the cell.

In Figure 24 is represented the BER in function of the received Doppler shift for a SNR of 20dB and 15kHz between subcarriers. As it can be observed the Bit Error Rate is constant for Doppler shift frequencies below 7.5kHz but for a higher Doppler shifts the ML estimator fails.

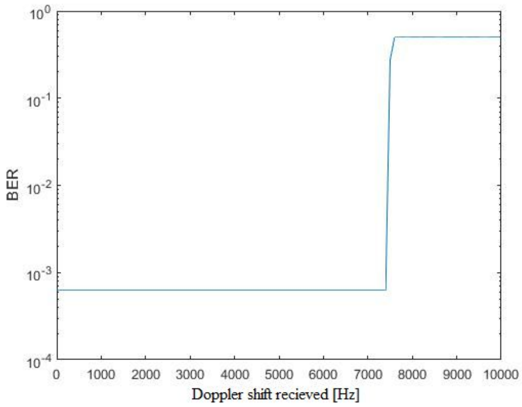

Figure 24: BER in function of the received Doppler

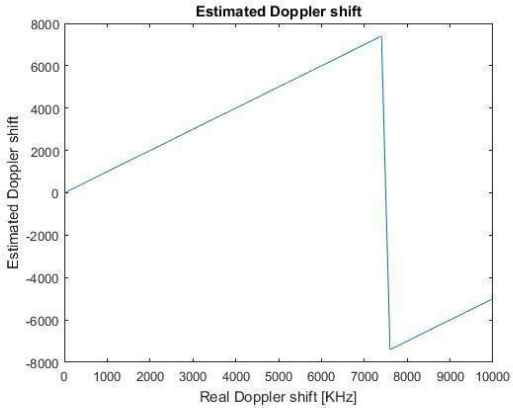

Figure 25: Estimated Doppler shift

Its observable how the phase of the Doppler shift estimated change in 7.5kHz. This change is produced because the space between subcarriers is 15KHz. If the Doppler shift is more than 7.5kHz there is Inter-carrier frequency and the orthogonality is destroyed.

With a space between subcarriers of 15KHz causes that the radius of the cell be bounded between 0km and the maximum radius of the cell depends of the carrier frequency transmitted. For a a f_0=1GHz the maximum radius of the cell is 305km or 152km for a 2GHz carrier frequency.

The next figure shows the BER as function of the Doppler shift received with a subcarrier spacing of 30KHz. The ML estimator can estimate the double range of frequencies due the space between subcarrier has augmented two times. Now the maximum Doppler ship than the receiver can tolerate is 15KHz.

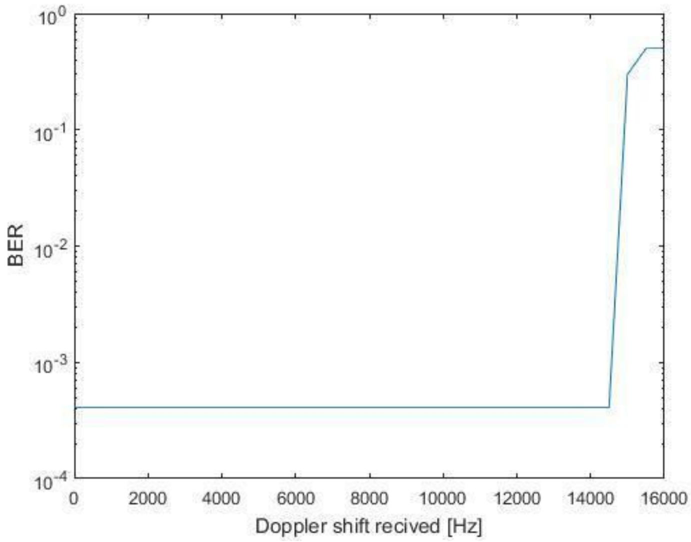

Figure 26: BER in unction of the Doppler observed with a 30kHz subcarrier spacing

One possible solution is to increment the subcarriers space to 30kHz, now the maximum radius of the cell for a f_0=1GHz is 610km.

6. Budget

This is a theoretical project based made with software support. In this section there is analyzed the costs of the full project. The main costs of the project are software licenses and hours of work.

Item	Cost
Standard Matlab License	2000€
IEEE database	
CubeSat ToolBox (Matlab) Princeton Satellite Systems	495€
TOTAL	2495€

Table 3: Software and IEEE papers cost

An estimation of the number of hour that I have dedicated to the project are presented in the following table. The cost are evaluated for an junior engineer at a price of 8€ hour.

	Hours	Cost
Create OFDM Signal	60h	480€
Create orbital model	40h	320€
Characterize Doppler Shift	120h	960€
Characterization of the channel	40h	320€
Define possible solutions	100h	800€
TOTAL	360h	2880€

Table 4: Estimation of the worked hours

The total cost of the project are:

TOTAL COST	5375€

Table 5: Total cost of the project

7. Conclusions and future development:

Now a days, remote rural areas, undeveloped countries and maritime zones don't have connectivity to broadband networks. With the implementation of the LEO communication systems this problem will be resolved in most of the cases. Furthermore, when there is a natural disaster the terrestrial base stations usually are affected isolating these areas. LEO communications systems can replace the terrestrial network in these emergency situation. Moreover can complement the terrestrial networks for traffic-loading in densificated regions. Integration of LEO networks in 5G is in the roadmap of 3GPP, Google, Facebook and some other companies. Global coverage is the new challenge for the coming years.

In this project I propose an strategy to compensate the Doppler shift that the ground-mobile terminals observe in a LEO communication system. As it explained in the project the Doppler shift is the change of the carrier frequency due the relative motion between the mobile terminal and the satellite. In this project the Doppler shift for a LEO communications is characterized and we can observe that is much higher than that tolerated by the LTE standard. The first strategy that is applied is to compensate this Doppler shift in the center of the coverage cell. Now the frequency offset in the center of the cell is zero but the residual Doppler in the extreme of the cell is not negligible. This residual Doppler is due to the difference of elevation angles that will see a terminal in the extreme with a terminal in the center of the cell. The points parallel to the trajectory will observe much Doppler shift due the elevation angle will change more quickly. To compensate this residual Doppler shift an ML Doppler shift estimator is implemented in the OFDM receiver. In order to estimate the Doppler that the terminal are receiving and in this way can do a correct demodulation.

Some results are presented in terms of Bit Error Rate to characterize the correct operation of the compensation strategy. As we can see, the BER curve in function of the SNR for the LEO communication system after applying the compensation strategy is approaching to the ideal with zero Doppler shift.

Finally the radius of the cell depends of the spacing between subcarriers. For the typical value of LTE standard this subcarrier spacing is 15kHz. With this spacing the maximum radius of the cell is 305km for a carrier frequency of 1GHz. Incrementing this spacing between subcarriers, the radius of the cell also will increment.

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