5G Positioning Reference Signal Configuration for Integrated Terrestrial/Non-Terrestrial Network Scenario

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***Abstract*—The Fifth Generation (5G) New Radio offers a new Positioning, Navigation, and Timing (PNT) service with larger signal bandwidth and higher frequency carriers than previous generations, delivering more accurate measurements. This allows other vertical industries to benefit from this feature, opening up new possibilities. Furthermore, the 5G network includes Non-Terrestrial Network (NTN) elements such as Unmanned Aerial Vehicle (UAV), High-Altitude Platform Systems (HAPS), and satellites, which are gaining significant attention from the industry to allow for global communication. The future 6G aims to create a single network entity with multiple connectivity layers for all devices in all scenarios.**

Therefore, when combining both aspects of the 5G networks, the PNT service, and the NTN, there are several benefits such as: an independent and complete communication and navigation system under a single network, higher accuracy on the PNT solution than previous generation, global coverage for join navigation and communication, higher resilience on the positioning estimation, or new services offered. However, this is not free of challenges, as it is expected to achieve an accuracy, at least, similar to Global Navigation Satellite System (GNSS). One of the challenges is the multiplexing of the data and positioning service using a single infrastructure such a satellite.

This paper has the purpose of analysing the effect in the accuracy of a delay estimator when a satellite constellation send a Positioning Reference Signal (PRS). Assuming that all satellites share the same frequency carrier and are synchronised between them. This 5G PRS main characteristic is its flexibility in terms of resource usage such as bandwidth, resource element density, symbols periodicity, a muting scheme, etc. This flexibility will be exploited in this paper to get a UE capable to estimate the Downlink Observed Time Difference of Arrival (DL-OTDoA) of the signal. Two challenges are present in this work, both are related to the characteristics of the RF channel between the Next Generation Base Station (gNB) and the User Equipment (UE): the first one is how the UE will cope with the high Doppler shift due to the high speed of the Low Earth Orbit (LEO) gNB increasing the Inter-Carrier Interference (ICI); and the second challenge is the effect of variable delay between OFDM symbols in the same slot and transmitter, increasing the effect of Intersymbol Interference (ISI).

The contribution of the authors on this paper is the analysis of different PRS configuration that keeps a low interfere level between the moving gNBs. The result of this research highlight the impact that the length in number of subcarriers and number of OFDM symbol has in the accuracy of the delay estimation. It shows a trade-off in the constellation design, as a higher number of satellites in visibility also increase the ICI and ISI.

***Index Terms*—PNT, delay estimation, NTN, 5G**

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I. Introduction

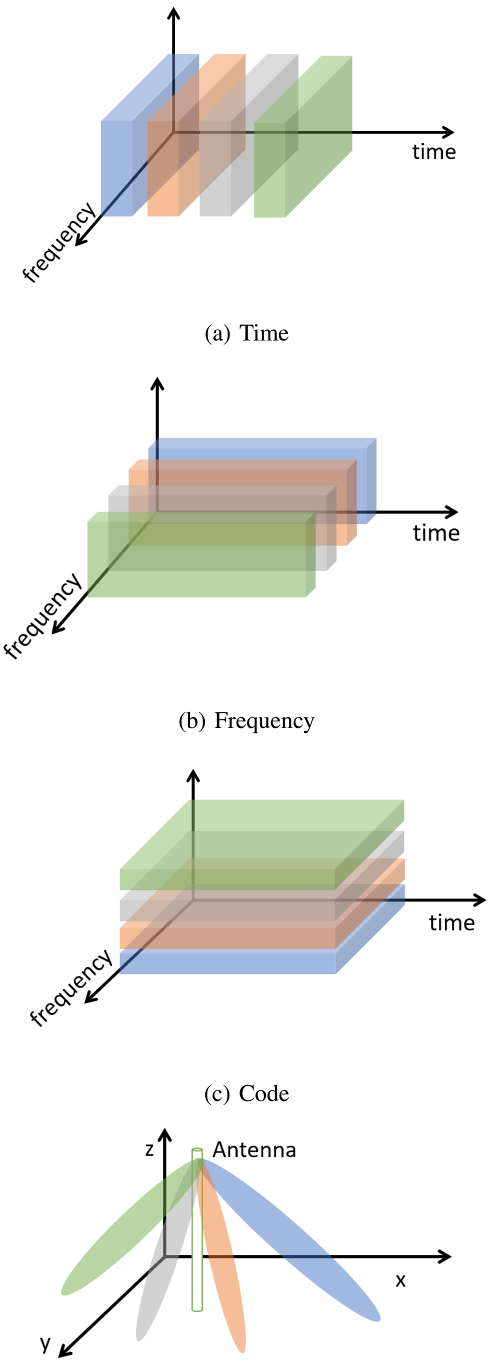
A system designed for localizing an asset needs to gather several measurements to solve the localization equations. These measurements can be obtained in two ways, from a single anchor [1] or from multiple anchor [2]. Besides, the measurements obtained from these anchors can be of different nature, such as Doppler shifts, delays, angles of arrival/departure, etc.

A well known example of multiple anchors system is GNSS, where each satellite transmit a signal, a receiver obtain these signals from multiple satellites and the receiver estimates its position and time. On these systems, all the anchors share a common resource (time, frequency, code, space...) that needs to be orchestrated between them. In particular, the Global Positioning System (GPS) L1 satellites transmit a signal at the same time (assuming no synchronization error between satellites) using the same frequency carrier. However, each satellite has a different and unique code. Therefore, the multiplexing of the signal in GPS is by using orthogonal codes.

In the 5G networks, exist a signal defined for localization of UE, it is called PRS. This signal can be used to determine the Time of Flight (ToF) of a transmission, or the beam where it is transmitted (and therefore the angle of departure) [3]. This PRS bring to the 5G positioning service the flexibility to multiplex the signal on different domains such as:

- **Time**: Its possible to select what Orthogonal Frequency-Division Multiplexing (OFDM) symbol carries the PRS. Different gNBs can send the PRS at different symbols or slots.
- **Frequency**: Each gNB configure the PRS by assigning different offsets in the subcarriers of a OFDM symbol, therefore not colliding at the transmission time.
- **Space**: Each gNB can send different PRS in different beams.
- **Code**: Each PRS is generated with a different seed or ID, similar as the Pseudo-Random Noise (PRN) code on GPS. This ID can be used to identify the gNB which transmit this signal.

For the reader not familiar with these multiplexing techniques, the following Figure 1 represent an example of 4 different transmission multiplexed in different domains.



(a) Time

(b) Frequency

(c) Code

(d) Space

Figure 1: Four Techniques for multiplex 4 channels

Figure 2 represent a 5G New Radio (NR) slot Resource Block (RB) with the PRS of 4 different gNB in different positions, assuming a perfect synchronisation. The Resource Grid (RG) time (x axis), and frequency (y axis) is shared between this 4 gNBs [1]. Then, at the receiver side, is possible to retrieve information related with the transmission of each gNB as they are orthogonal in time, frequency and code.

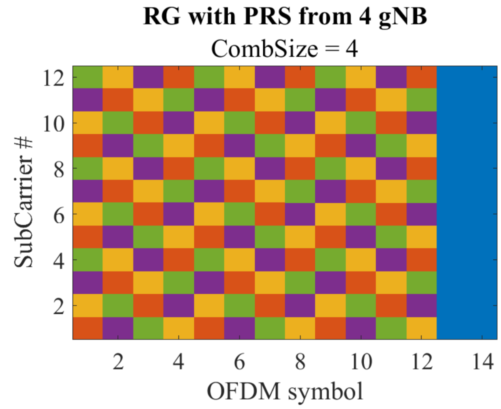


Figure 2: OFDM slot Resource Grid shared between 4 transmitters

However, the channel will apply to the signal some impairments such Doppler shift, delay, attenuation, multipath, etc. Each technique of multiplexing has different benefits and disadvantages, depending on the predominant impairment that the channel apply. Some analysis has been done on this topic, for example Chen et al on the reference [4] made a theoretical analysis of the ISI and ICI on a OFDM signal, however their results where based on the Bit Error Rate (BER), and on this paper we are interested in the accuracy of a delay estimator. Also Thomas et al in [5] made an analysis of a OFDM receiver however, they assumed fixed satellites only. On this paper we show the effect that different multiplexing techniques -time and frequency- have in the delay estimation accuracy when the channel is from a LEO satellite. For this analysis, we designed a scenario where a UE receives multiple transmissions of the PRS from a NTN LEO constellation of gNB. These transmissions are multiplexed with different techniques, time, frequency and code as shown in Figure 1 and the results shows the dependency between the accuracy of the delay estimation and the kind of multiplexing technique evaluating the Signal-to-Noise Ratio (SNR), and the time to compute a delay estimation.

This paper is organised as follows, in Section II we explain the signal model, the scenario designed, and the methodology used to evaluate these Key Performance Indicator (KPI). Then, in Section III we detail the simulation, show the results obtained and a discussion about them. Finally, in Section IV we highlight how the estimator can be improved on this scenario and future research on this topic.

II. Methodology and Scenario Definition

A positioning system has several metrics to evaluate its performance. Some of them are: latency (time between the

[1] Each colour is a different gNB

request and the answer for the position estimation), availability (percentage of time where the UE can get enough measurement to compute the position with enough accuracy), or scalability (maximum number of UE the system can serve). In this paper we focus the analysis on the accuracy that a UE can achieve and the performance in terms of processing time.

The delay estimation accuracy can be determined by its percentile (for example the 95%), or by the variance of the estimator $\sigma^2 = \mathrm{E}[(X-\mu)^2]$). Where X is the delay estimation and μ is the mean value. On this paper we will evaluate both parameters, the percentile and the variance for different multiplexing options and PRS configurations.

Besides, in the literature exists different lower bounds for unbiased estimators such as Ziv-Zakay [6] or Cramer-Rao (CRLB) [7]. We will also compare the results obtained by simulations with the theoretical Cramer-Rao lower bound. The rationale for choosing the CRLB is that it is adequate to model Gaussian processes, even though it is accurate with higher SNR values than the Ziv-Zakay bound [8].

A. Theoretical model description

The downlink signal model with PRS embedded can be represented in its complex base-band form as:

$$x_c(t) = \sqrt{\frac{2C}{N}} \sum_{n=0}^{N-1} b(n) \exp{(j\frac{2\pi nt}{T})} \quad (1)$$

Where:

- C: Power of the base-band signal
- N: Total number of Sub-Carriers
- $b(n) = d(n)p(n)$: symbol transmitted at the n-th subcarrier composed by the data or pilots $d(n)$ and its relative power weight $p(n)^2$. This power is constrained by $\sum_{n=0}^{N-1} p(n)^2 = N$
- T: is the OFDM symbol period

Then, for the channel model we follow the 3rd Generation Partnership Project (3GPP) Tapped Delay Line (TDL) model. Described in the reference [9] by:

$$h_c(t) = \sum_{k=0}^{L_C-1} h_k \delta(t - t_k - t_\epsilon) \quad (2)$$

Where:

- L_C Are the total numbers of channel taps. This number varies according to the 3GPP model profile. On the reference [10] the reader can find the details of the four profiles, two for Non-Line of Sight (NLOS) and two for Line of Sigh (LOS)
- h_k is the complex gain of the kth path of the channel. These channel coefficients are time varying with a Rice (for LOS) or Rayleigh (for NLOS distribution and follows a classical Jakes Doppler Spectrum defined by the maximum Doppler shift
- δ is the Dirac delta function
- t_k is the relative delay between the first path and the kth path
- t_ϵ is the delay of the first path

Then the received signal after removing the Cyclix Prefix (CP) and assuming perfect frequency synchronization is modelled as:

$$y_C(t) = x_C(t) * h_C(t) + n_C(t) \quad (3)$$

Where:

- $*$ is the convolution operation
- $n_C(t)$ is Additive White Gaussian Noise (AWGN)

This signal received, is then sampled at F_s sampling rate or $T_s = 1/F_s = T/N$. After, the receiver apply a N-points Discrete Fourier Transform (DFT) to obtain the OFDM symbols:

$$r(n) = \sqrt{2C} b(n) H(n) + w(n) \quad (4)$$

Where:

- $r(n)$ is the OFDM symbol
- n is the subcarrier index
- $H(n) = \mathcal{F}(h_d(m))$ is the discrete frequency response of the channel. Where $\mathcal{F}$ is the DFT and $h_d(m)$ is the discrete channel response from $h_c(t)$
- $w(n)$ $\mathcal{N}(0, \sigma_W^2)$ is the discrete AWGN

This signal can be expressed in vector notation as the sum of each transmission:

$$\mathbf{r} = \sum_{i=0}^{M} \mathbf{B}_i \mathbf{\Gamma}_{\tau_i} \mathbf{F}_L \mathbf{h}_i + \mathbf{w} \quad (5)$$

Where:

- $\mathbf{r} = [r(-N/2+1), ..., r(N/2)]^T$ are the OFDM samples received with N subcarriers.
- $\mathbf{B}_i = \sqrt{2C}\mathrm{diag}(b(-N/2+1), ..., b(N/2))$ is the matrix with the PRS pilots transmitted by the i-th gNB with $i \in [0, ..., M]$.
- $\mathbf{\Gamma}_{\tau_i} = \mathrm{diag}(e^{-j\frac{2\pi}{N}(-N/2+1)\tau}, ..., e^{-j\frac{2\pi}{N}(N/2)\tau_i})$ is the effect of the delay τ in all subcarriers. Assuming the delay is constant along the T_s duration.
- $\mathbf{F}_L$ are the first L columns of the zero-frequency centered DFT matrix.
- $\mathbf{h} = [h_0, ..., h_{L-1}]^T$ are the L taps channel model coefficient.
- $\mathbf{w} = [w(-N/2+1), ..., w(N/2)]^T$ is the noise vector.

The interference due to the Doppler effect is called ICI and the long delay from the LEO satellite is called ISI. This ISI appears due to the fact that the CP added into the OFDM signal after the Inverse Fast Fourier Transform (IFFT) process is not long enough to cope with the long delay variation that a receiver from LEO experiences. Following the theoretical development done by Chen in [4] we model the reception of the PRS as a sum of different contributions, the interference created by the other satellites and the self interference created by its movement (Doppler and long delays).

$$\mathbf{r}(k) = \mathbf{S}(k) + \mathbf{D}(k) + \mathbf{S}_p(k-1) + \mathbf{C}(k) + \mathbf{w} \quad (6)$$

Where:

- $\mathbf{r}(k)$ are the N samples of the k-th OFDM symbol received
- $\mathbf{S}(k)$ model the PRS sent in the OFDM symbol k
- $\mathbf{D}(k)$ is the model for the Doppler interference or ICI
- $\mathbf{S}_p(k-1)$ represent the contribution the previous OFDM symbol adds to the interference at symbol k due to the delay longer than the CP in the same transmitter
- $\mathbf{C}(k)$ correspond to the interference contribution of other satellites
- $\mathbf{w}$ is AWGN

The combined interference is modelled with the $\mathbf{D}(k)$, $\mathbf{S}_p(k-1)$, and $\mathbf{C}(k)$ parameters. This parameters contain the pilots $b(n)$ of the PRS from the same satellite or other satellites, where our signal of interest is $\mathbf{S}(k)$. On our scenario, the multiplexing of different satellites in frequency and time is done by the subcarrier and symbol position of the PRS as shown in Figure 2. Assuming that at the time of transmission all satellites are synchronised. However, the channel apply a different delay and Doppler to each transmitter, creating the possibility for one symbol interfere with the previous in time, or the frequency shift of each subcarrier not to be enough losing the orthogonality.

B. Methodology to evaluate the receiver

The receiver model is based on a two steps scheme:

1) A coarse joint Doppler and delay estimation based on the correlation of the received signal and a local copy of the PRS pilots. This method is based on a search grid of two axis: Doppler and delay. The delay axis has a size $[0, n]$ with $n < N$, where n is the number of samples of the received signal block and N the number of samples of the reference signal. The Doppler search domain is $\pm\frac{\text{SC}}{2}$ where SC is the subcarrier spacing.
   After the coarse delay and Doppler are estimated, the signal is compensated for this delay and Doppler ready to be used in the second step.
2) The previous correlation method has a delay resolution of T_s (Symbol time), thus, a fine estimation of the delay is needed. It is obtained by two different procedures with the idea of comparing them:
   a) Maximum Likelihood method, it is described in Equation 7, and is based on the work done by Del Peral et al in the reference [9], where the delay of each transmitter is estimated by:

   $$\hat{\tau} = \arg\min_{\tau} \parallel (\mathbf{I} - \mathbf{A}_\tau(\mathbf{A}_\tau^H\mathbf{A}_\tau)^{-1}\mathbf{A}_\tau^H)\mathbf{r} \parallel^2 \quad (7)$$

   Where:
   - $\mathbf{A} = \mathbf{B}_i\mathbf{\Gamma}_\tau\mathbf{F}_L$

   These parameters are explained in the Equation 5.

   b) A interpolation of the correlation between the local reference and the compensated signal. This interpolation of the correlation method is done only on a sampled window centered in the peak of the correlation. This interpolation method uses a cubic procedure as it has similar performance as spline method but uses much less resources. The size of this window is 10 samples and the interpolation factor is 100. These values are selected to give an accuracy of 1% of a symbol time.

In order to evaluate the different multiplexing methods for the PRS, we model each contribution to the ICI, ISI and interference from other satellites as a Gaussian random variable. For the ICI we set $\mathbf{D}(k) = \mathcal{N}(0, \max(f_{Doppler}))$, then the ICI is modelled as $\mathbf{S}_p(k) = \mathbf{S}(k) \times \mathcal{U}(0,1)$ as a uniform random variable representing the percentage the previous symbol interfere with the actual symbol. The other satellite interference is modelled as $\mathbf{C}(k) = M \times \mathcal{N}(0, \max f_{Doppler})$ as M the max number of satellites on LOS from the UE.

III. Results

The performance of the delay estimator is gathered via a Monte Carlo simulation with $1280 = 128 \times 10$ iterations [2]. On each iteration the transmitted PRS symbols pass through the channel $\mathbf{h}$ and, at the receiver side, is combined with the effect of: the ISI from the adjacent symbol, the ICI due to the Doppler shift, the interference from other satellites that can be in LOS with the user, and the multipath of each transmission.

First, we show the performance of both delay estimators when there is only one satellite transmitting the PRS, to set it as a baseline to compare then with different number of satellites and see the effect on the estimators' performance.

A. Single satellite

Starting from a single satellite transmitting the PRS, we highlight different KPI to asses their performance.

Table I: Execution time of the two delay estimators

Estimation method	Execution time(ms)
Interpolation	0.336
Maximum Likelihood	62.3

The first metric to evaluate is the execution time of each delay estimation method in Table I. The reader can see the benefit of using the interpolation method. The time to get an estimation is more than an order of magnitude lower due the small number of operations for the windowed interpolation than using the Maximum Likelihood.

This KPI is crucial in devices where the latency of the estimation is of utmost importance, such as high speed vehicles. Also it can be beneficial as the device using the interpolation can average more measurements than using a ML approach to get a robust estimation.

The next KPI evaluated is highlighted in Figure 3, where its compared the behaviour of both estimators in different SNR conditions. It is noticeable that they perform almost equally until the region of high SNR, where the interpolator outperform the Maximum Likelihood estimator. Furthermore,

[2] The machine used for the simulation has 128 cores

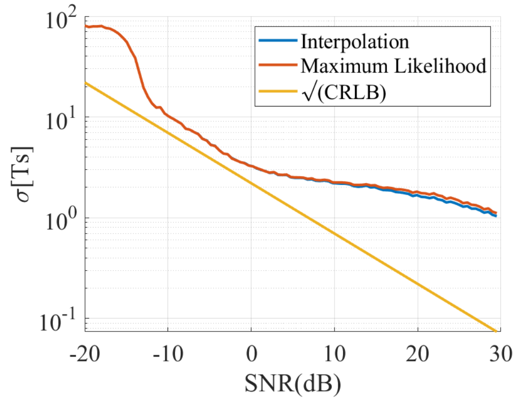


Figure 3: σ of the estimator vs the SNR of the received signal

as a matter of comparison, it is added to the graph the Cramer-Rao Lower Bound (CRLB) of a channel model AWGN as a lower bound. Both estimators does not attain the CRLB as the channel model used is more complex than a simple AWGN, and is out of the scope of this paper to obtain the CRLB for a multipath, multi-symbol, and multi-transmitter scenario. However it can serve as a coarse comparison with the lowest limit that can be achieved. On our channel model, all the impairments the channel add, are reflected as a distance from this lower bound.

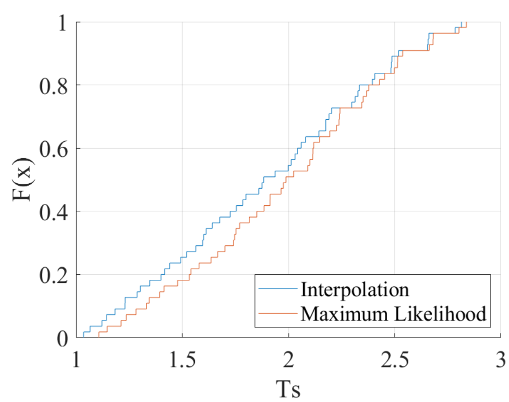


Figure 4: Empirical Cumulative Density Function of the estimators

Another method to compare the performance of an estimator is by its Empirical Cumulative Density Function (ECDF), as we present in Figure 4. It shows in the X-axis the delay estimation error in Ts units, and in the Y-axis the CDF of the MonteCarlo simulation. The better performance is again using the interpolation estimator, as for the same percentil, the blue line has less error than the red one. These result, added to the previous one in Table I demonstrate that the fine delay estimation using a cubic interpolation is a good solution in terms of accuracy and latency.

B. Multiple satellites

On this subsection, the delay estimator has a increased challenge to obtain an accurate result, as the desired signal is mixed with different transmission. This multiplexing in frequency (Each satellite transmit in a different subcarrier) is affected by the Doppler shift, where in the previous subsection the subcarriers that did not carry the PRS where empty. Now that all subcarriers are occupied, the Doppler shift and different delays makes that those unwanted transmission interfere with the signal of interest.

Table II: Performance of the estimators depending the number of satellites in LOS

N Satellites in LOS	**σ[Ts]**	
	Interpolation	ML
1	1.296	1.464
2	1.613	1.752
4	3.834	3.853
6	1.4220e+05	1.4219e+05

The previous Table II shows the performance of the same delay estimators with: a fixed SNR of 20 dB[3], an effective bandwidth of 144 subcarries and one symbol transmitting the PRS. This effective bandwidth means that the length of the PRS sequence is fixed to 144 Resource elements per satellite, the total bandwidth of the signal is the aggregation of the different transmissions. If there is 2 satellites, the total bandwidth is 288 subcarriers as each satellite transmit its PRS, but effective still 144, and so on, as shown in the Figure 2 for the case of 4 transmitters.

These results highlight the higher performance of the interpolation method against the Maximum Likelihood method up to having 4 satellites on LOS. Increasing the number of satellites in view also increases the interference among them. Degrading the performance of the estimator as the Table II shows, reaching the point that with 6 satellites, the estimation cannot be trusted without using a more complex receiver. This contribution should be taken into account when designing a PNT service where the UE needs to be very simple or low cost, such as Internet of Things (IoT). If these UE are limited in computing power, the interpolation method present a good choice as a delay estimator.

However, this situation can be improved by leaving some subcarriers unused, "cleaning" the received signal from interference of other satellites, in other words, in the Figure 2 some of the Resource Elements can be left unused. For that reason, the PRS in 5G has a mutting scheme, where the transmitter can switch off the transmission for certain slots and certain symbols.

IV. Conclusions

This research highlight the complexity and trade-offs in the design of a PNT system using a LEO satellite constellation. To address this situation, the designer should start with the

[3]Between the signal of interest and the AWGN noise, not the interference created by the other satellites

accuracy expected by the service, then, obtain the minimum bandwidth to get this accuracy and then analyse the different sources of interference, such as ISI and ICI, that will degrade the performance. A way to reduce the effects of the ISI and ICI, is by the use of the muting scheme of the PRS. Other technique to reduce the ISI and ICI is found in the work of Negash et al in [11], where they substitute the Fourier Transform for a Wavelet Transform. The next step on this topic is to analyse the muting scheme commented in the final results, when a moving gNB is transmitting the PRS. As it moves, using a fixed scheme for the Resource Grid scheduling as a multiplexing scheme is not optimal. The use of the muting scheme, plus the position of the satellite, the ComSize of the Resource Grid and accuracy requested, lead to an interesting join optimization problem to minimise the interference created between the satellites and maximise the accuracy provided.

Furthermore, in our scenario we assumed that all gNB were perfectly synchronised, that is not the real case, as Prol et al reported in [12], opening another research topic in this line, analysing the effect on the ISI and ICI when the satellites are not perfectly synchronised.

Finally, the latest research for positioning came by the developments of super-resolution delay estimators such as ESPRIT, that has been used by Lapin et al in [13] or machine learning techniques as mentioned by Mogyorosi et al in [14]. These techniques open a new area of research where their feasibility for low power devices needs to be further investigated.

Appendix. Acronyms

This paper makes use of an extensive number of acronyms, to help the reader, the following list shows all of them:

5G	Fifth Generation
3GPP	3rd Generation Partnership Project
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CP	Cyclix Prefix
CRLB	Cramer-Rao Lower Bound
DFT	Discrete Fourier Transform
DL-OTDoA	Downlink Observed Time Difference of Arrival
ECDF	Empirical Cumulative Density Function
GPS	Global Positioning System
gNB	Next Generation Base Station
GNSS	Global Navigation Satellite System
HAPS	High-Altitude Platform Systems
IFFT	Inverse Fast Fourier Transform
IoT	Internet of Things
ICI	Inter-Carrier Interference
ISI	Intersymbol Interference
KPI	Key Performance Indicator
LEO	Low Earth Orbit
LOS	Line of Sigh
NLOS	Non-Line of Sight
NR	New Radio
NTN	Non-Terrestrial Network
OFDM	Orthogonal Frequency-Division Multiplexing
PNT	Positioning, Navigation, and Timing
PRN	Pseudo-Random Noise
PRS	Positioning Reference Signal
RB	Resource Block
RG	Resource Grid
SNR	Signal-to-Noise Ratio
TDL	Tapped Delay Line
ToF	Time of Flight
UAV	Unmanned Aerial Vehicle
UE	User Equipment

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