



## 5G Communication with a Heterogeneous, Agile Mobile network in the Pyeongchang Winter Olympic competition

Grant agreement n. 723247

# Deliverable D5.3 Ubiquitous sub meter accuracy positioning with Galileo and wireless network features

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Abstract
This document is an intermediate version. It analyses and defines the 5G interoperability architectural framework integrating GNSS based technology. It also describes the methods to enable accurate positioning by using Galileo features and radio access with high carrier frequency, large antenna arrays and large bandwidth. Last, it specifies a test bed to demonstrate the performance in test cases representative of selected usage conditions.

Index terms
Positioning, 5G, GNSS, mmWave, Interoperability, Galileo



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## List of Acronyms

5G	5 <sup>th</sup> Generation
ALASSO	Adaptive - LASSO
AOA	Angle Of Arrival
AOD	Angle Of Departure
BS	Base Station
DGNSS	Differential GNSS
DOP	Dilution Of Precision
GMM	Gaussian Mixture Model
GNSS	Global Navigation Satellite System
HPBW	Half Power BeamWidth
KPI	Key Performance Indicator
LASSO	Least Absolute Shrinkage and Selection Operator
mmWave	Millimeter Wave
MIMO	Multiple Input – Multiple Output
MS	Mobile Station
PoC	Proof-of-Concept
PPP	Precise Point Positioning
RTK	Real Time Kinematic
SIMO	Single Input – Multiple Output
SNR	Signal to Noise -Ratio
WRTK	Wide RTK
UE	User Equipment
ULA	Uniform Linear Array
URA	Uniform Rectangular Array



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## 1 Introduction

This document analyses and defines the 5G interoperability architectural framework integrating GNSS based technology.

Section 2 describes the methods to enable accurate positioning by using GNSS and Galileo features.

Section 3 describes the methods to enable accurate position with high carrier frequency, large antenna arrays and large bandwidth in the millimeter-wave (mmWave) band.

Section 4 defines a mixed GNSS/mmWave solution to cope with multipath in urban environments.

Section 5 specifies a test bed to assess the performance in representative test cases, along with the expected results.



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## 2 GNSS positioning

This section describes how GNSS positioning can reach sub-meter accuracy. It starts by enumerating the positioning error sources, then it details the various techniques to get rid of these errors and to select the most suitable, and finally it provides the benefits brought by Galileo and 5G to GNSS positioning.

### 2.1 Positioning error sources

A GNSS receiver collects signals emitted by the GNSS satellites in its field of view. Then, with correlation techniques applied to these collected signals, the receiver estimates the ranges from the satellites. These ranges are called “pseudorange” because they are affected by errors from various main sources. The table below lists these error sources along with their typical range error and highlight the ones that are mitigated with precise positioning techniques.

Error source	Origin	Typical range error	Mitigated with precise positioning techniques
<b>Satellite clock</b>	Even if the timing equipment of GNSS satellites is very precise and corrections are broadcasted in the GNSS signal, a small clock bias still remains.	1 m	✓
<b>Satellite ephemeris</b>	A GNSS satellite broadcast its own position within the signal, but with a limited accuracy.	1 m	✓
<b>Ionosphere and troposphere</b>	Signals from the GNSS frequency band are subject to delays in these atmospheric layers.	11 m	✓
<b>Multipath</b>	GNSS signals are reflected and delayed by ground infrastructures and vegetation.	2 m	✗
<b>Receiver noise</b>	Thermal noise generated by the receiver RF.	0.1 m	✗
<b>Receiver clock</b>	Mass-market receivers contain oscillators cheaper than the ones on-board the satellites. However, because all GNSS signals are similarly affected by the receiver clock, this error is easily mitigated by the receiver during the computation of the position.	N/A (removed by receiver)	N/A



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## 2.2 Precise positioning techniques

In order to be able to reach a sub-metric positioning accuracy, these errors should be the most possible mitigated. Many techniques have been developed using an additional GNSS receiver, which is fixed and whose position has been precisely determined. This additional receiver (called a “reference station”) collects GNSS signals like a classical receiver, with which corrections can be applied since the exact position of the station is known. The errors that can be mitigated by these corrections are the following:

- Satellite clock
- Satellite ephemeris
- Ionosphere and troposphere

Multipath cannot be mitigated by a reference station since it is a very local source of error, and the receiver noise cannot be corrected either because it is specific to each GNSS receiver.

Thanks to all these corrections, sub-metric accuracy can be achieved if the receiver is placed in an open-sky environment that is not subject to strong multipath.

Two methods coexist to generate and provide corrections: Precise Point Positioning (PPP) and Differential GNSS (DGNSS). The following subsections will detail each of them and select the best one adapted to mass-market receivers.

### 2.2.1 Precise Point Positioning (PPP)

With the PPP method, reference stations are networked in order to combine their measurements and to compute very precise satellite clock, ephemeris, and optionally ionosphere/troposphere corrections. Any receiver, even far from a reference station, can benefit from these corrections with an Internet access, because the corrections calculated with the PPP method are independent from the position of the reference stations. The networks are either free of charge and managed by public organisations like the International GNSS Service (IGS), or commercial services requiring a subscription to be accessed (Novatel, NavCom...).

PPP data can also be provided by satellite link: this is planned for the future developments of Galileo [1]. However, the corrections would be transmitted on a separate sub-band (E6), which can only be received by multi-frequency receivers. Most of mass-market receivers are currently single-frequency because of cost matters, but affordable multi-frequency ones could appear in the following years.

In order to reach sub-meter accuracy, the receiver has to make carrier phase measurements instead of code phase measurements. Code phase processing uses the information of the satellite signal (the code) to compute the position, whereas carrier phase processing uses the radio signal (the carrier), which has a much higher frequency (see figure below).



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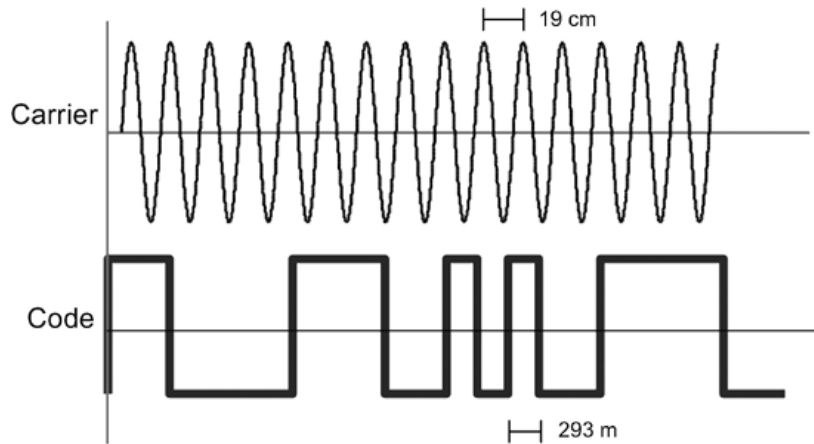


Figure 1: Illustration of the carrier and the code of a GNSS signal

However, the number of phase cycles for the carrier between the satellite and the receiver, which is unknown (contrary to the number of code cycles), has to be determined by the receiver: this is called “ambiguity resolution”. The ability to resolve ambiguity depends on the signal C/N0 and on multipath: an open-sky environment is clearly more adapted than urban environment where multipath is omnipresent. Because of this ambiguity resolution step, PPP will have a long convergence time, often above 5 minutes as shown in the figure below extracted from a test campaign in Thales Alenia Space premises.

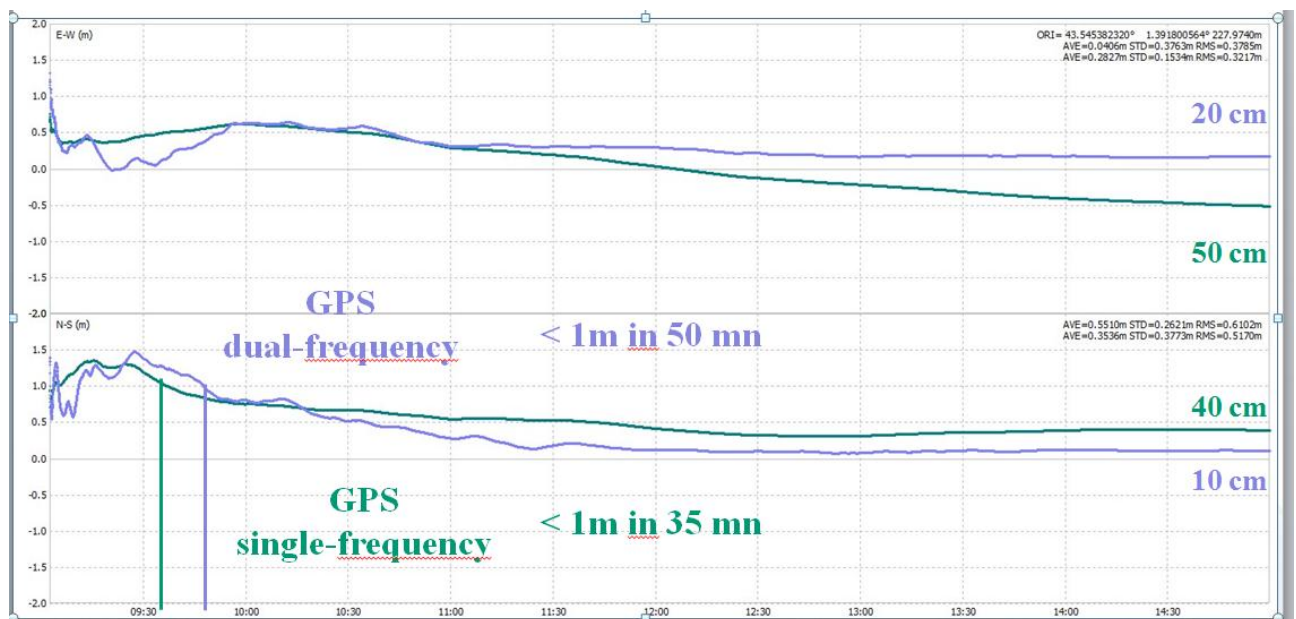


Figure 2: Time to reach 1 m accuracy with the PPP method for GPS single or dual frequency

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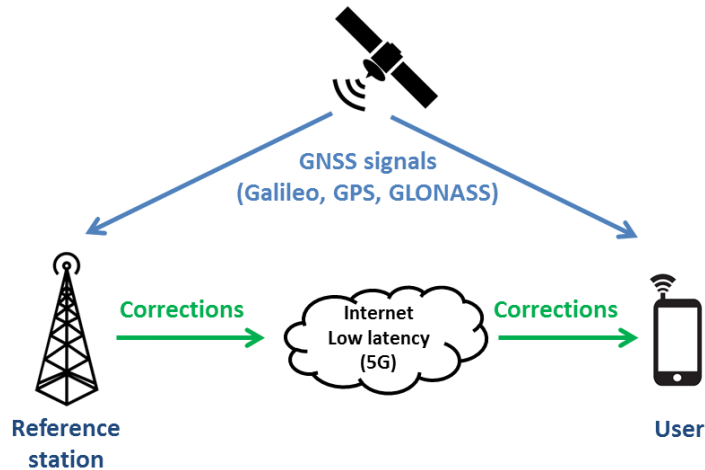
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*Figure 3: PPP technique*

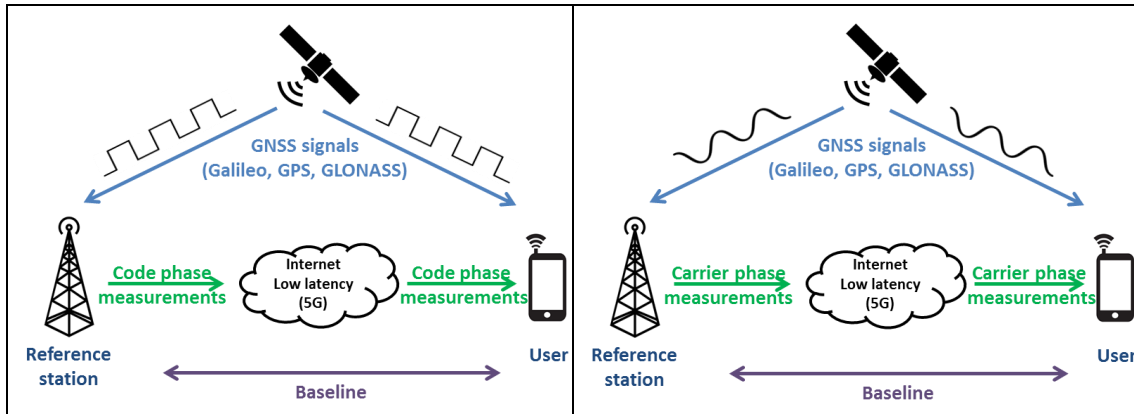
### 2.2.2 Differential GNSS (DGNSS)

Contrary to PPP, reference stations in DGNSS are independent and do not communicate with each other. Instead, the reference station broadcasts its pseudorange measurements, which are used by the user's receiver to mitigate clock, ephemeris troposphere and ionosphere errors. The corrections apply only in the vicinity of the station: the positioning accuracy of the DGNSS method can be less than 1m if the baseline (distance from the receiver to the reference station) is less than a few tens of kilometres.

There are two main DGNSS methods: standard and Real Time Kinematic (RTK), depending on the type of measurement that is used.

With standard DGNSS, the user's receiver computes its position with algorithms based on code measurements of the GNSS signals from the reference station and the user itself (Figure 4, left), contrary to RTK algorithms, which are based on carrier phase measurements (Figure 4, right).

Like the PPP technique (see above), RTK leads to a better accuracy because of these carrier phase measurements, but it is as well subject to the ambiguity resolution issue. However, the ambiguity will be resolved much faster than for PPP thanks to the phase measurements of the reference station that are transmitted to the user's receiver.



**Figure 4: Standard DGNSS (left) and RTK (right)**

### 2.2.3 PPP, standard DGNSS and RTK trade-off

The table below shows the main characteristics of the three methods:

	PPP	Standard DGNSS	RTK
Accuracy	< 1m	~ 1m	< 1m
Convergence	> 5mn	< 1mn	< 1mn
Availability	In open-sky areas	In open-sky areas	In open-sky areas
Baseline	Infinite	< 50 km	< 50 km
Bandwidth	< 10 kb/s	< 10 kb/s	< 10 kb/s
Service cost	Free	Free	Free

All the three GNSS positioning methods can be used free of charge and require a very low data rate. The very long convergence time of the PPP method makes it currently unsuitable for most usages, like pedestrian or road navigation (but techniques are under investigation to reduce the convergence time [4]), and standard DGNSS can hardly reach a sub-meter accuracy. On the other hand, the RTK method is very accurate, has a short convergence time and can be easily implemented in the next years: that is why it has been selected for demonstration in the scope of this project.

Indeed, all recent mass-market receivers have enough processing power to compute a position based on carrier phase measurements (the current issue is battery life) [2], and 5G would allow massive simultaneous connections all around the world to data from reference stations. These should form a quite dense network because the range from the user to the reference station should not exceed 50 km. However, a new technique currently in preliminary development called WRTK (for Wide RTK) creates virtual reference stations from an existing network to extend the use of RTK to areas which are in the range of any reference station. This WRTK technique would limit the number of reference stations to deploy in non-populated areas.

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### 2.3 Galileo: a great improvement for GNSS localisation

Before 2011, only GPS and GLONASS satellites were able to provide a positioning service above Europe. The on-going deployment of Galileo, the European GNSS constellation, and its support by recent mobile terminals, opens new perspectives for a more accurate and ubiquitous GNSS localisation for a wide range of users. Indeed, Galileo benefits from a number of technical improvements and new features compared to GPS and GLONASS systems. To name main benefits:

**Better availability and accuracy.** 31 GPS and 24 GLONASS satellites are currently in operation. As of today, Galileo add 11 more GNSS satellites, and the full operational constellation will be composed of 24 operational spacecraft.

Generally speaking, more satellites available to the user for localisation translates to a better positioning accuracy and a better availability of the positioning service, especially in zones with a limited sky view. This is shown by the figures below: to simulate an urban environment, the coordinates of Toulouse city have been set and satellites below 40° of elevation have been masked. With GPS and GLONASS, there are some time slots where less than 4 satellites are visible, which makes the localisation impossible. For instance, like shown in Figure 5: only 2 GPS and 1 GLONASS are available at time 15:10, but with Galileo two more satellites are added (yellow line) and localisation is possible.

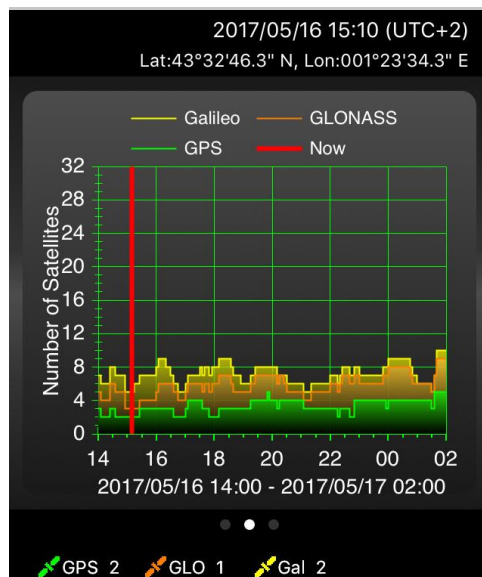


Figure 5: Number of visible satellites with a 40° mask

The dilution of precision (DOP) value reflects the effect of satellite geometry on the positioning accuracy (Langley, 1999). A high DOP means that the satellites used for positioning are closed to each other, limiting the accuracy (Figure 6).

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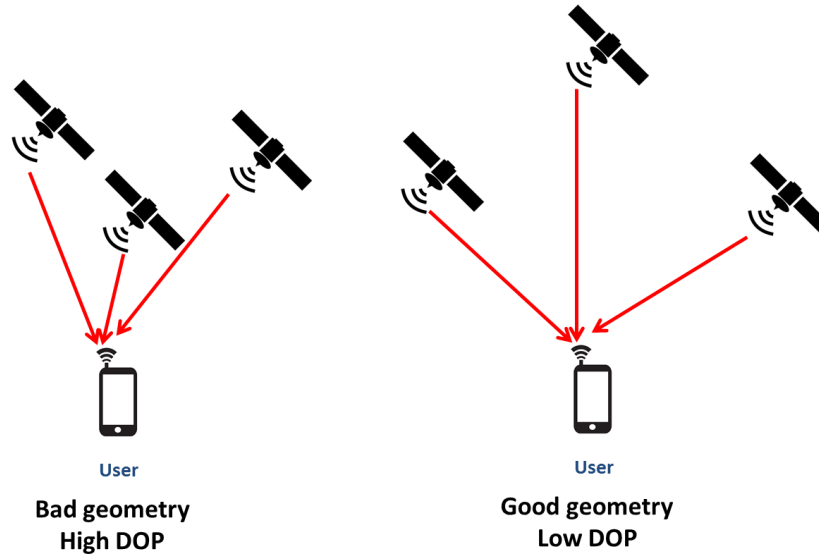


Figure 6: Satellite geometry and DOP

The introduction of the Galileo constellation also significantly improves the positioning accuracy in zones with a limited field of view by reducing the DOP, as shown in Figure 7: the DOP drops from 13.6 to 7.5 when Galileo is added.

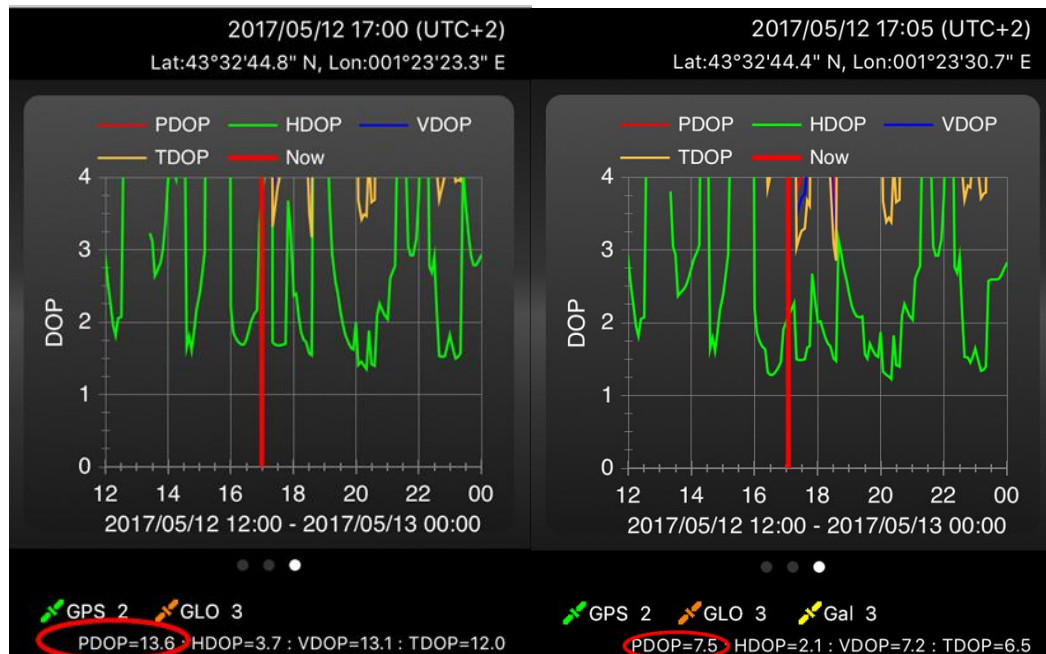


Figure 7: DOP with and without Galileo, 40° mask

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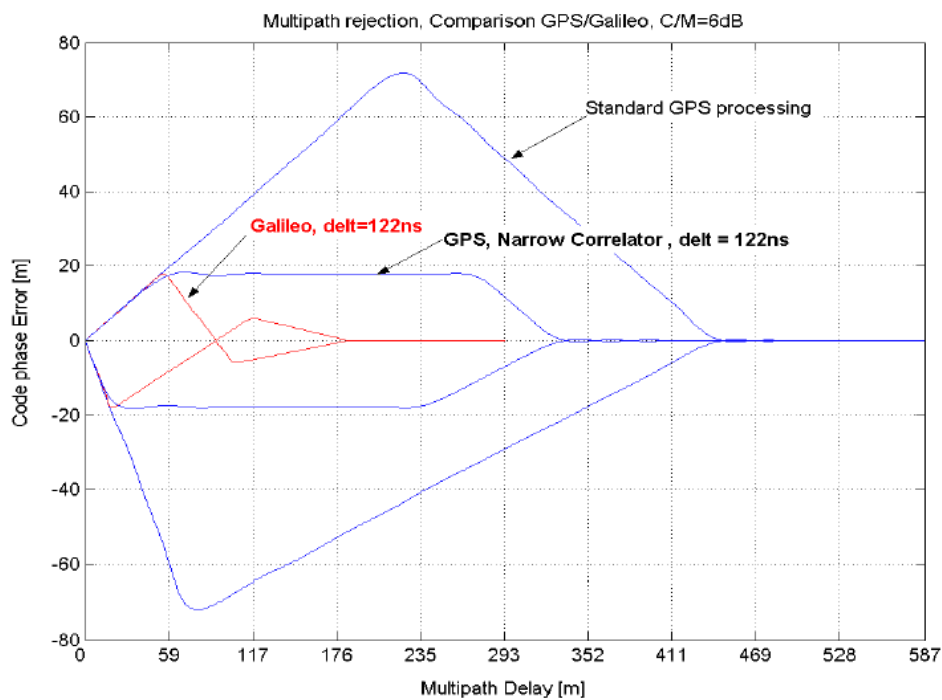
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**Robustness to multipath.** Galileo signals have been designed to be more resistant to multipath propagation, as shown by the theoretical multipath envelope in Figure 8: the code phase error is much lower for Galileo than for GPS.



**Figure 8: Code phase error in presence of multipath**

This is confirmed by measurements on the GNSS reference station in Oulu that will be used in the scope of this project:



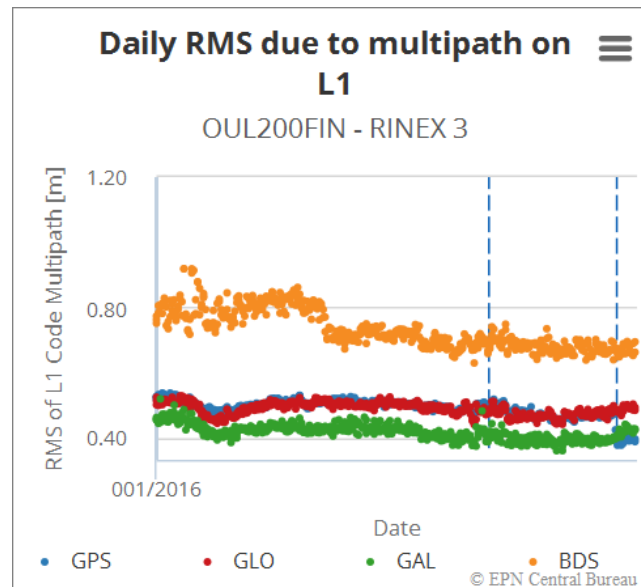
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**Figure 9:** RMS error due to multipath for various GNSS constellations

**Better Earth coverage.** The inclination of Galileo orbital planes was chosen to provide a better coverage at high latitudes, especially for operation over northern Europe, an area poorly covered by GPS.

## 2.4 5G: the ideal channel to transfer reference station data

Ephemeris are coded and transmitted by the satellites in their navigation signal, but with a very low data rate: a receiver doing a “cold start” should wait up to two minutes to get the position of all visible satellites. To speed up this process, mass-market receivers like smartphones usually download these ephemeris from the Internet: this is called A-GNSS.

With the 5G technology, according to [3], several hundreds of thousands of users could be simultaneously connected to the same 5G station. This increased capacity compared to 3G or 4G networks could be used to disseminate RTK corrections from nearby reference stations to all users at the same time and with a very short latency. The 5G channel would not be overloaded by this RTK link because it requires a data rate of only a few kb/s.



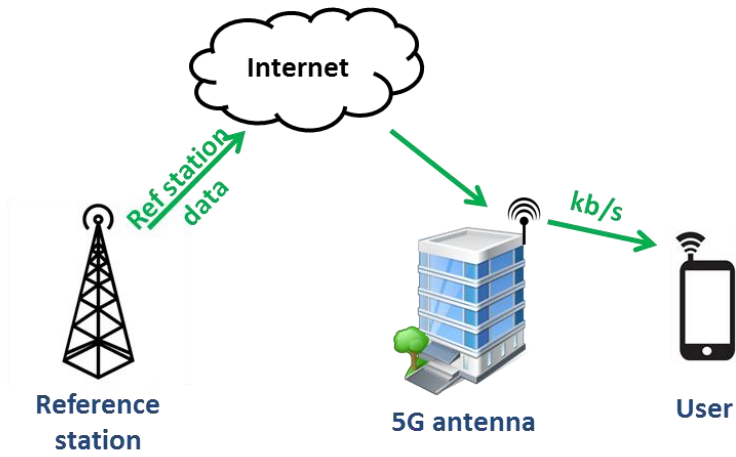
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*Figure 10: Use of 5G network for reference station data*



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## 3 mmWave positioning

### 3.1 Concept

In this Section, we introduce the concept of millimeter-wave (mmWave) technology for positioning application for future (5G) radio systems and discuss about the tunable parameters on those.

The mmWave technology<sup>1</sup> is considered as one of the key properties of the next generation (5G) communication networks. The communication system based on mmWave can take an advantage of two important properties introduced by the mmWaves: First, it allows high data rate and secondly the utilization of large antennas (a large number of elements on antenna array) for massive multiple-input-multiple-output (MIMO) system [P2, P3]. Thus one important feature, beamforming, can be utilized via the large antenna arrays [P4].

Rest of the Section is organized as follows, first in Section 3.2, we describe the system model, namely channel model and antenna model assumed at receiver and transmitter, and furthermore describe the beamtraining method. Then in Section 3.3, we describe the positioning method given the channel estimation results.

### 3.2 System model

#### 3.2.1 System overview

The proposed mmWave positioning technique is based on the single basestation (BS) system, and thus it consists only one receiver and one transmitter radio (in one mobile user case). Each radio part is described in more detail in 5GChampion document [IR2.1], namely components:

- 5G antenna system (including antenna array and computing unit) which provides the beam information to be used to calculate the link-based position at the server;
- The server that provides the beam information (angular information) upon user request.

In the following, we will introduce shortly the mmWave MIMO radio channel, antenna model, and beamforming principle to utilized in the proposed algorithm.

#### 3.2.2 mmWave MIMO communication model

Consider a mmWave single-user MIMO wireless system. The location of the transmitter, base-station (BS), and the receiver, user equipment (UE) (or mobile-station (MS)), are denoted by  $\mathbf{q} \in \mathbb{R}^2$  and  $\mathbf{p} \in \mathbb{R}^2$  in the given coordinate system, respectively. We assume that the location of BS  $\mathbf{q}$  is known, whereas the location of MS  $\mathbf{p}$  is not. Furthermore, the rotation of BS is assumed to be  $0^\circ$  (related to the common reference system) while MS has an unknown rotation denoted by  $\alpha$ . Thus, BS and MS have different orientation with respect to a common reference system. The line-of-sight (LOS) view from BS to MS is denoted by  $\varphi$ , and from MS to BS (accounting rotation) by  $\theta$  (note that rotation  $\alpha$  is related through  $\alpha = \pi - \theta + \varphi$ ). The model is illustrated in Figure 11 with 2D antenna array of BS and MS

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<sup>1</sup> A radio frequency band of 30 – 300 GHz via exact definition. Although relaxed definition are e.g. from 23 – 32 GHz bands [P1].



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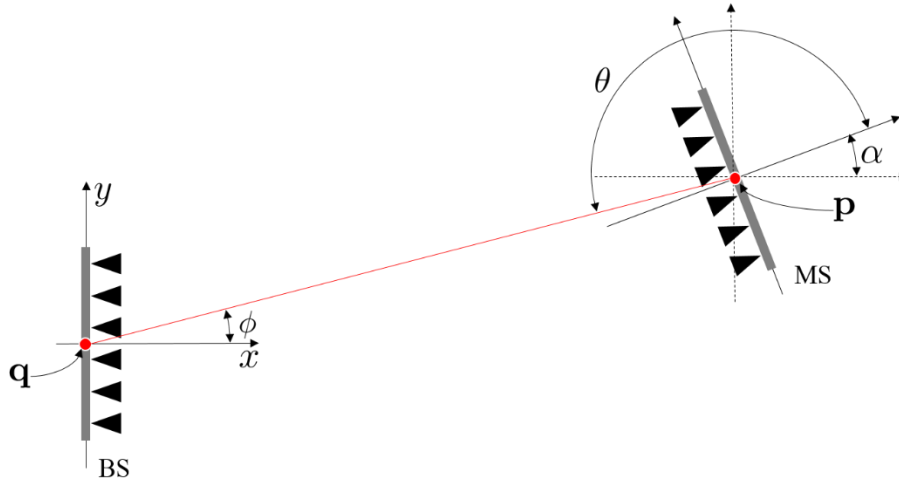
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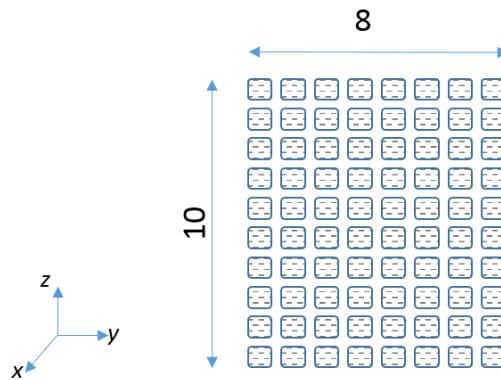
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positioned at afore mentioned location  $\mathbf{p}$  and  $\mathbf{q}$ , respectively. MS has unknown orientation  $\alpha$  relative to BS.



**Figure 11: Geometry of the MIMO communication**

We consider that both transmitter and receiver are equipped with uniform rectangular array (URA) with  $M_y \times M_z$  and  $N_y \times N_z$  isotropic elements on the BS side and MS side, respectively. Extension to 3D antenna array is straightforward, but to easen the notation as well as to match the antenna types that will be used in 5GCHAMPION proof-of-concept (PoC) demonstration platform, the model is described with 2D antennas. An example of URA antenna with  $M_y = 8$  and  $M_z = 10$  is illustrated in Figure 12.



**Figure 12: Uniform rectangular array (URA) antenna model**

The URA antenna array coefficient for given path azimuth  $\theta$  and elevation  $\phi$  matrix  $\mathbf{A}$  is given as

$$a(u) = [e^{-j2\pi u_2(m-1)}]_{m=1,\dots,M_y} \otimes [e^{-j2\pi u_3(n-1)}]_{n=1,\dots,M_z}$$

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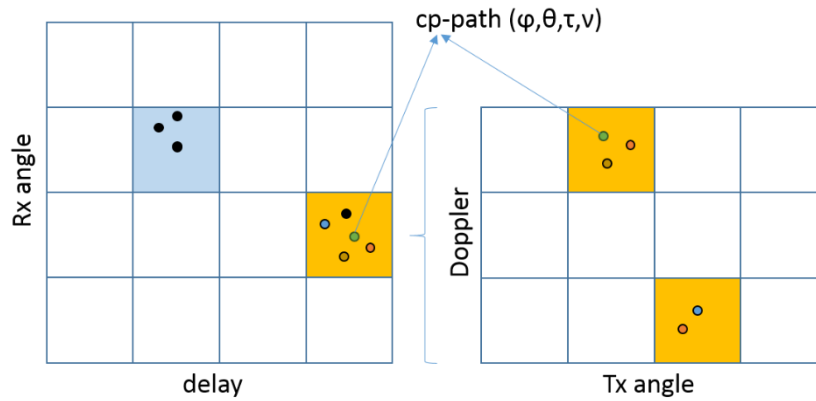
where

$$u = [0, |\cos \theta \sin \phi|, |\sin \theta|]$$

Furthermore, we assume in the following antenna element separation  $d = \lambda/2$  element separation, where  $\lambda$  is the carrier wavelength. Antenna implementation technologies are discussed on detail 5GCHAMPION deliverable D3.1.

### 3.2.3 Channel model

We assume a channel model, where radio paths can be presented as a set of clustered paths. This *sparsity* induced channel model is illustrated in Figure 13, where first 2 dimensions are depicted (on the left side), namely the received side angular domain and time delay component, and then two more dimensions are depicted (on the right side) for one cluster on those domains, namely transmitter side angular domain and Doppler domain. [P5]



**Figure 13: Sparse channel representation as a 4-dim tensor**

Now, the full-dimensional channel model can be presented as 4-dimensional tensor:

$$\underbrace{\mathcal{H}}_{4D\text{-tensor}} = \sum_{c=1}^C \sum_{p=1}^{P_c} b_{cp} \underbrace{\mathbf{v}_r \left( \frac{\mathbf{P}_r^T \mathbf{u}_{r,cp}}{\lambda}; M \right)}_{\text{RX spatial frequency}} \circ \underbrace{\mathbf{v}_t \left( \frac{\mathbf{P}_t^T \mathbf{u}_{t,cp}}{\lambda}; N \right)^*}_{\text{TX spatial frequency}} \circ \underbrace{\mathbf{v}_f \left( \frac{\tau_{cp} W}{N_{\text{FFT}}}; N_{\text{FFT}} \right)}_{\text{DFT-frequency}} \circ \underbrace{\mathbf{v}_d \left( \frac{\nu_{cp} T_0}{T}; M_d \right)}_{\text{Doppler frequency}}$$

where each tensor-component is sum of  $P_c$  paths in total of  $C$  clusters, where each path is given as function of radio path coefficient  $b_{cp}$ , array factors  $\mathbf{v}_r$  and  $\mathbf{v}_t$ , for receiver and transmitter side, respectively, and Doppler frequency vector. Note that the Rx and Tx spatial frequency components are function of transmitter and receiver position  $\mathbf{P}_r$  and  $\mathbf{P}_t$ , and  $M, N$  are 'total' number of antenna elements.

Then as a mmWave channel can be seen via “quasi”-optical propagation properties [P6], we assume a single-path MIMO channel  $\mathbf{H}$  given by



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$$\mathbf{H}(\theta, \phi) = h a_R(\theta) a_T(\phi), \quad (1)$$

where  $h$  is the dominant channel coefficient, and  $a_R(\theta)$ ,  $a_T(\phi)$  are the transmit and receive array response vectors for the angle-of-departure (AoD)  $\phi$  and angle-of-arrival (AoA)  $\theta$ .

Then the received signal  $y$  can be written as a function of angular domain or as a function of relative position vector  $\mathbf{p}$  as

$$\begin{aligned} y(t) &= \sqrt{P_{tx}} h \mathbf{w}^H \mathbf{a}_M(\theta) \mathbf{a}_N^H(\phi) f_x(t - \tau) + \mathbf{w}^H \mathbf{n}(t) \\ &= \sqrt{P_{tx}} h \mathbf{w}^H \hat{\mathbf{a}}_M(\mathbf{p}, \alpha) \hat{\mathbf{a}}_N^H(\mathbf{p}, \alpha) f_x(t - g(\mathbf{p}, \alpha)) + \mathbf{w}^H \mathbf{n}(t) \end{aligned} \quad (2)$$

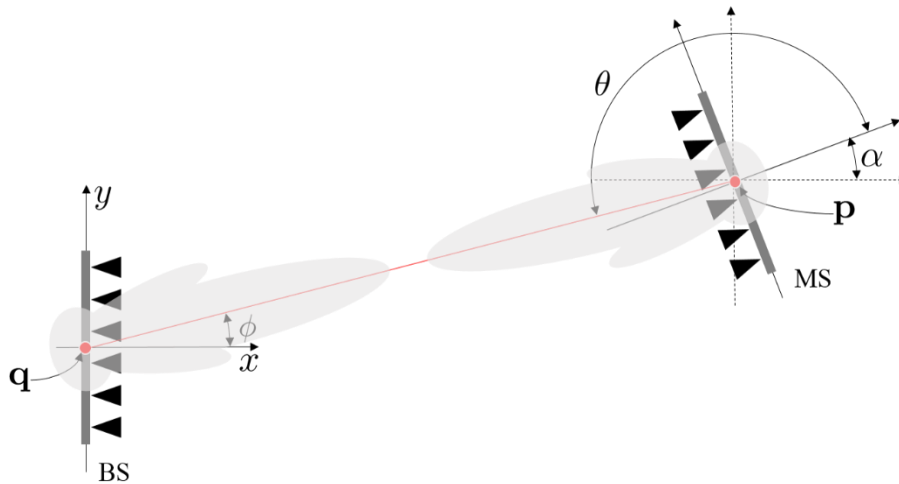
where the MS location defines the parameters on second form

$$\begin{bmatrix} p^x \\ p^y \\ \alpha \end{bmatrix} = \begin{bmatrix} q^x + c\tau \cos(\phi) \\ q^y + c\tau \sin(\phi) \\ \pi + \phi - \theta \end{bmatrix} \quad (3)$$

and  $\mathbf{w}$  and  $\mathbf{b}$  are beamforming vectors from the given codebook,  $P_{tx}$  is transmitted power and  $\tau$  is path delay. Beamforming procedure and codebooks associated to that, are discussed in the next Section.

### 3.2.4 Beamforming

In this Section, we present two beamforming strategies, namely an exhaustive and a hierarchical strategies. Exhaustive strategy is used as a solution with *less risks*, keeping mind on the real life demonstration and tests, as hierarchical strategy is used as a more realistic from the point of view of real life performance requirements. Our study of the trade-off between positioning and data rate is reported on D3.5.



**Figure 14: Illustration of the beamforming concept**



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Figure 14 illustrates the concept of beamforming, where perfect beamforming results to the perfectly aligned beams to both direction: from BS and MS and vice-versa.

### 3.2.5 Positioning Protocol

In this Section, we describe the proposed 5G positioning protocol. Communication occurs over frames of duration  $T_f$  of which a time  $T_t$  is devoted to beamtraining, *i.e.*, determining the best  $\mathbf{w}$  and  $\mathbf{f}$ . Then the remainder  $T_d = T_f - T_t$  is used for data transmission. The frame structure is illustrated in Figure 15. The frame allocation between the data-rate and beamtraining is result in a trade-off: More time is given for the beamtraining process, less time there is for the data transmission within a slot. Then on the other hand, more time there is for beamtraining, better the beam alignment will be, which in will improve the achieved data rate. This trade-off is investigated and reported in D3.4.

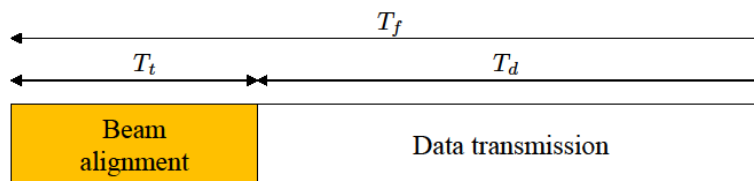


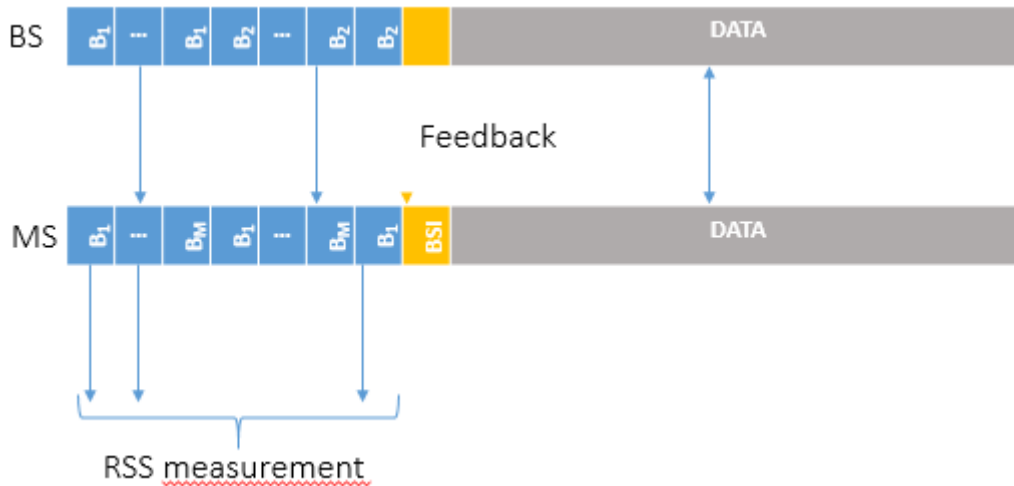
Figure 15: Training and Data transmission time trade-off

### 3.2.6 Beamforming and location

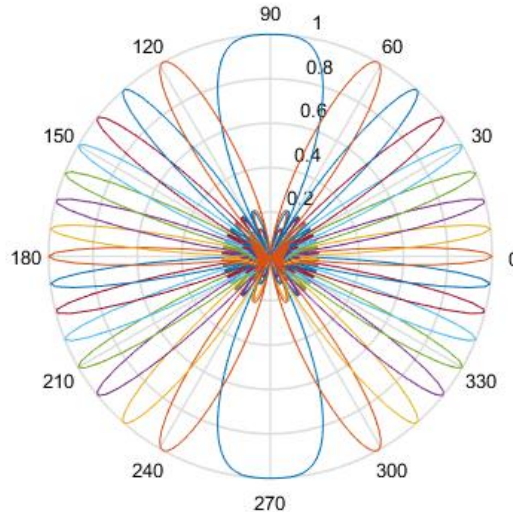
In this Section we describe an exhaustive and a hierarchical beamtraining strategies. For simplicity, we assume that the codebook dictionaries at the receiver side and the transmitter side are equal.

#### 3.2.6.1 Beamforming Exhaustive Search

In the exhaustive beamtraining strategy, both, receiver side and transmitter side codebooks are orthogonal, for instance, specific columns from the Discrete Fourier Transform (DFT) of  $N$ -size matrix, where  $N$  is number of antenna elements. The example of orthogonal beams derived from the DFT codebook is illustrated in Figure 17. The beamtraining mechanism consists of sounding all possible transmit-receiving pairs of beams and, for each pair, measure the receiving power. After all beam-pairs have been scanned, then the receiver informs the transmitter about the beam-pair index corresponding to the maximum receiving power. The beamtraining allocation is illustrated in Figure 16.



**Figure 16: Exhaustive search beamtraining allocation on a radio frame**



**Figure 17: Illustration of the beams from DFT codebook with 16 beams**

### 3.2.6.2 Beamforming: Hierarchical Search

In the hierarchical beamtraining strategy, receiver and transmitter side codebooks are generated based on a *nested partitioning* of the angular domain. In other words, we start by partitioning the whole angular domain, e.g.,  $[-\pi/2, \pi/2]$ , in  $K$  bins. For each bin, we design a beamformer such that the half power beamwidth (HPBW) coincides with the upper and lower bounds of the bin. Next, each angular bin is further partitioned in  $K$  bins and, a new set of



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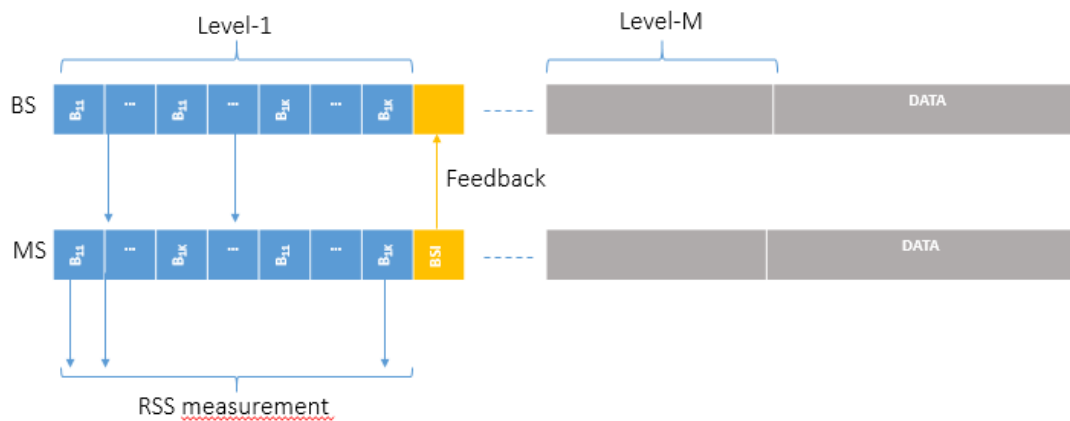
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beamformer is constructed. It results, that  $L = \lceil \log_K N \rceil$  partitioning (also referred to as level) are performed and at for the l-level,  $K_l$  beamformer vectors are defined. The example of codebooks for different levels of  $K = 0, 1, 2, 3$  is illustrated in Figure 19.

The hierarchical search strategy seeking for the link with the highest SNR is performed as divide-and-conquer algorithm. Namely, base station (BS) and mobile station (MS) start with an exhaustive search mechanism using the  $K$  beamformers of level-1. Based upon the measured receiving power, a new exhaustive search with the  $K$  beamformers of level-2 is performed. This procedure iterates until beamformers of level- $L$  are utilized. The beamtraining allocation of this strategy is illustrated in Figure 18.



**Figure 18: Hierarchical search beamtraining allocation on a radio frame**



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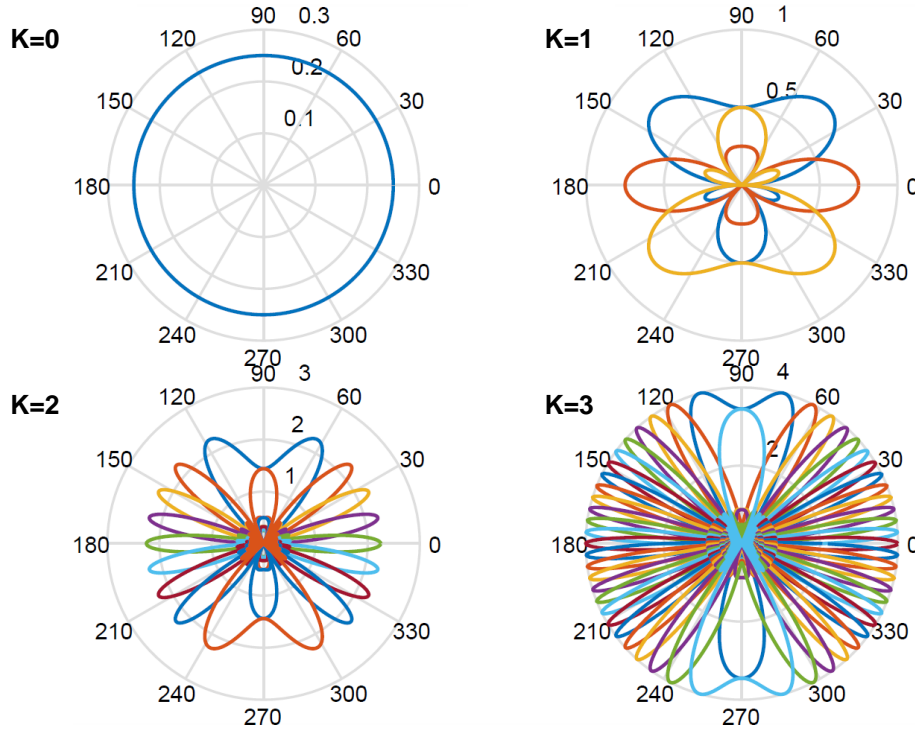


Figure 19: Illustration of the beams from the proposed hierarchical codebook design

### 3.3 From Channel Estimation to Position Estimate

In this Section, we describe a technique to derive position estimate from the channel estimation parameters. The key technique to employed is a channel estimation from the set of dictionary elements, *atoms*, via updating, *i.e.*, adapting the set of atoms to the existing radio channel during the estimation process. To ease the formulation, we consider a MISO link alternative to the MIMO in following derivation.

First, let us consider the user location  $\mathbf{x}$  as a function of location of BS denoted by  $\mathbf{b}$ , Line-of-Sight (LOS) path-delay  $\tau$ , and azimuth  $\bar{\phi}$  and elevation  $\bar{\theta}$  angle of arrival corresponding the LOS path

$$\mathbf{x} = \mathbf{b} + r [\cos(\bar{\phi}) \cos(\bar{\theta}), \sin(\bar{\phi}) \cos(\bar{\theta}), \sin(\bar{\theta})]^T,$$

where  $r$  is path-delay converted to the range estimate via  $r = c \tau$ , given the speed-of-light constant  $c$ . Now we can formulate the position estimation problem on the received signal  $\mathbf{Y}$  as

$$(\hat{\mathbf{x}}, \hat{\Delta}, \hat{\beta}) = \min_{\beta \in \mathbb{C}^L, \mathbf{x} \in \mathbb{R}^3, \Delta \in \mathbb{R}^{3 \times L}} \|\mathbf{Y} - \mathbf{W}^H \mathbf{A}^H \mathcal{H}(\mathbf{x}, \Delta) \mathbf{X}\|_2^2,$$

where the symbol  $\Delta$  accounts estimation error from true  $\mathbf{x}$  to the estimated  $\hat{\mathbf{x}} = \mathbf{x} + \Delta$ ,  $\beta$  is channel coefficient, and  $L$  is the number of components each channel vector  $\mathbf{h}$  is decomposed. The difficulties to solve the minimization problem is discussed in [P7], where the authors propose an indirect approach, in which the channel parametrization given in [P6],



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[P9] is exploited to generate a set of position estimate images and from where the final estimate of  $\mathbf{x}$  is based on the cluster of images associated to the LOS link.

The procedure is shortly summarized in the following. To begin with, Let us consider the vectorized form of the channel  $\mathbf{h} = \Psi \mathbf{z}$ , where  $\Psi$  is referred to as *dictionary* and  $\mathbf{z}$  is the representation of  $\mathbf{h}$  in  $\Psi$  [P6]. Now a single *atom* is a column vector of this dictionary (and corresponds to the vectorization of a multidimensional spatial-temporal discrete Fourier frequency).

Furthermore, we define a *dictionary function*  $\mathcal{D}$  as

$$\Psi = \mathcal{D}(\Xi)$$

which translates the dictionary variables to the atoms in dictionary.

Dictionary function is defined as a Kronecker product of  $U$  vectors and discrete complex-frequency components  $\mathbf{v}$

$$\mathcal{D}(\Xi) \triangleq \left[ \bigotimes_{i=1}^U \mathbf{v}(\xi_{i1}, K_i), \dots, \bigotimes_{i=1}^U \mathbf{v}(\xi_{iL}, K_i) \right]$$

where the parameter  $U$  refers to the number of dimensions used to represent the spatial-temporal discrete frequencies and  $\mathbf{v}$  is the discrete complex-frequency

$$\mathbf{v}(x, K) = \left[ 1, \dots, e^{-j2\pi x(K-1)} \right]^T$$

For instance, if the MIMO-OFDM channel can be represented with a bi-dimensional spatial frequency and a mono-dimensional Fourier frequency,  $U$  equals to three. [P7]

Then a single location image, given the dictionary variable  $\xi_{il}$  from the channel estimation procedure, can be written

$$\tilde{\mathbf{x}}_l = \mathbf{b} + \begin{bmatrix} \frac{c\sqrt{1-u_{2l}^2}}{\Delta_f} \cos(\text{asin}(u_{1l}) \sec(\sin(u_{2l}))) u_{3l} \\ -\frac{c\sqrt{1-u_{2l}^2}}{\Delta_f} \sin(\text{asin}(u_{1l}) \sec(\sin(u_{2l}))) u_{3l} \\ -\frac{c\sqrt{1-u_{2l}^2}}{\Delta_f} u_{2l} u_{3l} \end{bmatrix}$$

where  $u_{il}$  is received from

$$u_{il} = \begin{cases} 2\xi_{il}, & 0 \leq \xi_{il} < 0.5, \\ 2\xi_{il} - 2, & 0.5 \leq \xi_{il} < 1. \end{cases}$$

As proposed in [P7], practical solution can be found via Adaptive-LASSO (A-LASSO) described in [P6], [P9]. Key points of the A-LASSO estimator is dictionary adaptation. First, the sparse coefficient, which can be seen as importance weights for the corresponding dictionary vectors, are used to resample the dictionary vectors. Then using new vectors replace each resampled vector with close parameters (grid). Dictionary vectors are updated until the required level of saturation is received. The example of the dictionary *atom* updates is illustrated in Figure 20. The example shows first the initial dictionary, where the elements are aligned on evenly spaced grid (upper left), then (upper right) each element on the grid is updated with its importance weight (black dots), and re-sampling method is used to calculate



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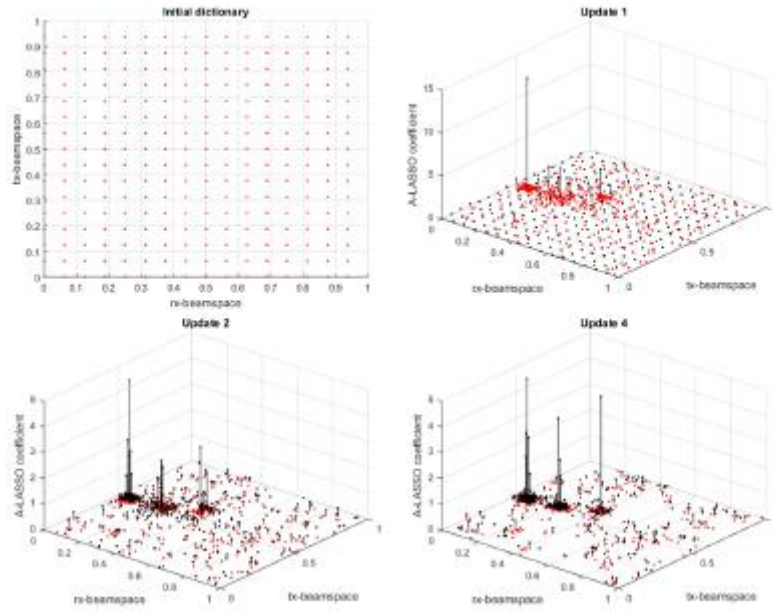
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the new set of atoms (red dots). Finally the step 4 (lower right) shows the atoms concentrated on the 3 locations on a beamspace.



**Figure 20: Four updates of dictionary column vectors inside the A-LASSO algorithm**

Finally the set of location images a classified via K-nearest algorithm or as proposed in [P7] via Gaussian Mixture Model (GMM) to identify strongest beamspace component as a LOS path. And the location estimate is location image of the atom with the highest importance weight as

$$\hat{\mathbf{x}} = \hat{\boldsymbol{\mu}}_s, \quad \text{with } s = \arg \max \gamma_i,$$

where  $\gamma_i$  is the weight of cluster  $i$  in the location image domain, and  $\hat{\boldsymbol{\mu}}_s$  is Gaussian Model parameter defining the cluster  $s$ . We utilize a classic Expectation-Maximization (EM) method to solve a classification problem. EM algorithm is well known, classical solution to the GMM problem. [P8]



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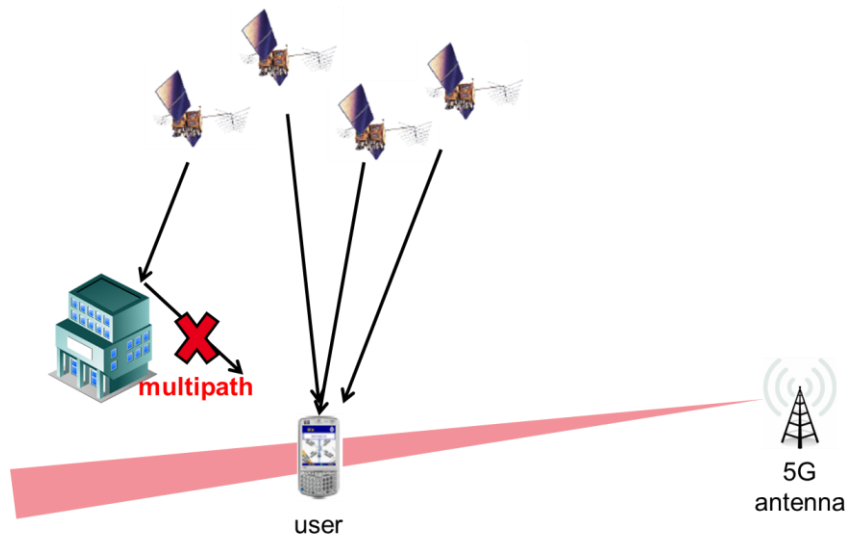
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## 4 Mixed GNSS/mmWave solution

### 4.1 Concept

This section describes the mixed positioning solution to be developed to cope with satellite availability and multipath in urban environment. It mainly relies on the pseudo-ranges provided by GNSS, with additional angular information provided by the 5G network that lowers the number of GNSS satellites required to compute a position and that can be used to dismiss GNSS signals affected by multipath (Figure 21).



*Figure 21: Mixed GNSS/mmWave solution*

In order to understand the solution using both GNSS and 5G network, a short description is first made about the GNSS positioning solution. Then the information provided by the 5G network is analyzed and finally it is included in the GNSS solution. As the 5G line of sight (LoS) information provides extra equations to solve the positioning problem, one can remove GNSS equations (i.e. satellites).

### 4.2 Algorithm description

#### 4.2.1 Position calculation

##### 4.2.1.1 Traditional GNSS solution

This section summarizes the steps to solve the equations used in GNSS positioning. The initial equations are as follows:

$$\rho_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} + c \cdot t_u$$

Where  $\rho_i$  is the distance between the  $i^{\text{th}}$  satellite and the user,  $(x_i, y_i, z_i)$  is the satellite position,  $(x_u, y_u, z_u)$  is the user's position and  $t_u$  is the user's clock bias.  $\rho_i$  is calculated by the

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receiver thanks to the time delay between emission and reception,  $(x_i, y_i, z_i)$  is provided through the navigation message, so  $(x_u, y_u, z_u)$  and  $t_u$  are the 4 unknowns. Therefore, at least 4 equations (i.e. 4 satellites) are needed to compute a solution.

The method to solve the system of equations is iterative: the position is assumed and at the end of the iteration, the computed position is closer to the real one. The variables  $\hat{\cdot}$  are the assumed ones.

$$\begin{aligned}\rho_u &= \hat{\rho}_u + \Delta\rho_u \\ x_u &= \hat{x}_u + \Delta x_u \\ y_u &= \hat{y}_u + \Delta y_u \\ z_u &= \hat{z}_u + \Delta z_u \\ t_u &= \hat{t}_u + \Delta t_u\end{aligned}$$

After this step, the unknowns are  $(\Delta x_u, \Delta y_u, \Delta z_u)$  and  $\Delta t_u$ . The initial equation becomes:

$$f(x_u, y_u, z_u, t_u) = \rho_i = \sqrt{(x_i - \hat{x}_u - \Delta x_u)^2 + (y_i - \hat{y}_u - \Delta y_u)^2 + (z_i - \hat{z}_u - \Delta z_u)^2} + c \cdot (\hat{t}_u + \Delta t_u)$$

In order to solve a linear problem which is easier, Taylor series are used up to the first term.

$$\begin{aligned}f(x_u, y_u, z_u, t_u) &\cong f(\hat{x}_u, \hat{y}_u, \hat{z}_u, \hat{t}_u) + \frac{\partial f(\hat{x}_u, \hat{y}_u, \hat{z}_u, \hat{t}_u)}{\partial \hat{x}_u} \Delta x_u + \frac{\partial f(\hat{x}_u, \hat{y}_u, \hat{z}_u, \hat{t}_u)}{\partial \hat{y}_u} \Delta y_u \\ &\quad + \frac{\partial f(\hat{x}_u, \hat{y}_u, \hat{z}_u, \hat{t}_u)}{\partial \hat{z}_u} \Delta z_u + \frac{\partial f(\hat{x}_u, \hat{y}_u, \hat{z}_u, \hat{t}_u)}{\partial \hat{t}_u} \Delta t_u \\ \rho_i &= \hat{\rho}_i - \frac{(x_i - \hat{x}_u)}{\hat{r}_i} \Delta x_u - \frac{(y_i - \hat{y}_u)}{\hat{r}_i} \Delta y_u - \frac{(z_i - \hat{z}_u)}{\hat{r}_i} \Delta z_u + c \cdot \Delta t_u\end{aligned}$$

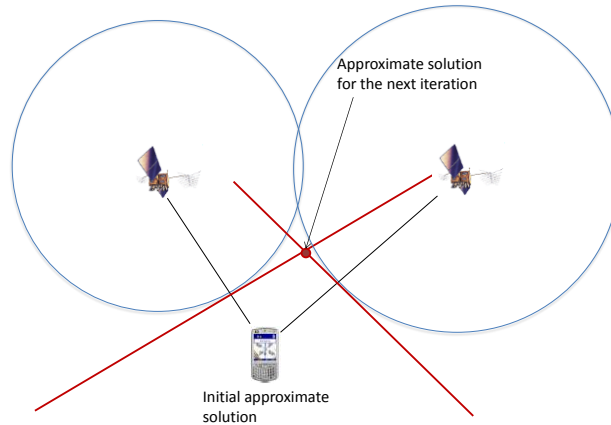
Where

$$\begin{aligned}\hat{\rho}_i &= \sqrt{(x_i - \hat{x}_u)^2 + (y_i - \hat{y}_u)^2 + (z_i - \hat{z}_u)^2} + c \cdot \hat{t}_u \\ \hat{r}_i &= \sqrt{(x_i - \hat{x}_u)^2 + (y_i - \hat{y}_u)^2 + (z_i - \hat{z}_u)^2}\end{aligned}$$

#### Intuitive explanation (no clock bias)

If one assumes that there is no clock bias and makes the substitution where  $(x_u, y_u, z_u)$  and  $t_u$  are the unknowns, the equation of a satellite represents the plane:

- tangent to the circle with the satellite at its center and of radius  $\rho_i$
- and perpendicular to the line of sight between the satellite and the assumed position.

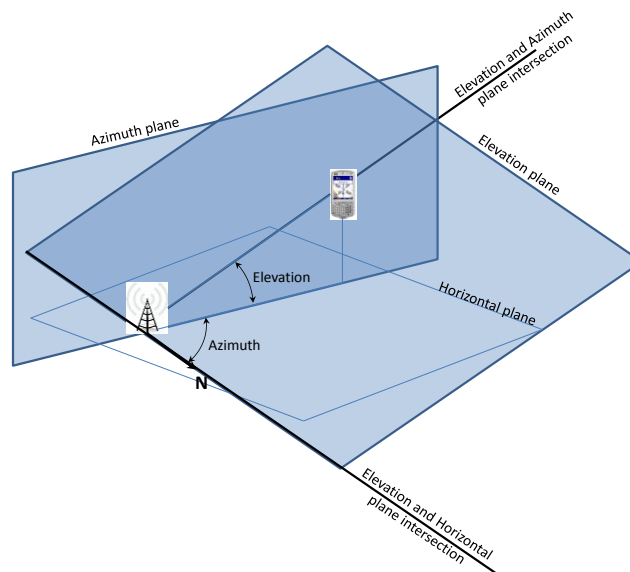


**Figure 22: Illustration of GNSS equations**

### 5G information to fit GNSS equations

5G antennas shall provide the direction towards the receiver that needs to be located. It is assumed that the azimuth and elevation angles are provided in real time and that the position of the 5G station is well known. With that information, one has to define one planes that will fit in the GNSS solution. The planes are described as follows:

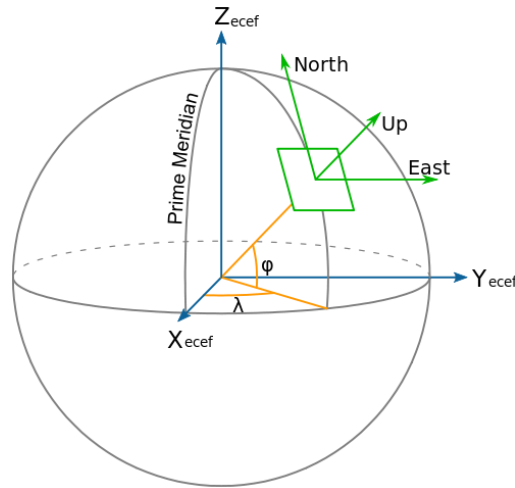
- Azimuth plane is a vertical plane in the local reference that contains the location of both the station and the receiver.
- Elevation plane is a plane perpendicular to the azimuth plane that contains the location of both the station and the receiver



**Figure 23: Illustration of 5G equations**



The planes can be calculated as follows in the ECEF frame:



**Figure 24: ECEF frame**

Let  $\vec{u} = (X_u, Y_u, Z_u)$  be the vertical vector at the station location. To complete the reference frame, the vector in the east direction will be:

$$\vec{e} = -\frac{(\vec{u} \times \vec{Z})}{|\vec{u} \times \vec{Z}|} = -\frac{\begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ X_u & Y_u & Z_u \\ 0 & 0 & 1 \end{vmatrix}}{|\vec{u} \times \vec{Z}|} = \left( \frac{-Y_u}{\sqrt{X_u^2 + Y_u^2}}, \frac{X_u}{\sqrt{X_u^2 + Y_u^2}}, 0 \right)$$

Where  $\vec{Z}$  is the vector in the Z direction in the ECEF reference. Then, the north vector completes the reference:

$$\vec{n} = \frac{(\vec{u} \times \vec{e})}{|\vec{u} \times \vec{e}|}$$

Once the local reference is set, it is easy to find the extra planes provided by the 5G antenna. Naming of the variables:

- $az$  is the azimuth angle
- $\vec{az}$  is the unitary vector in the direction of the receiver in the local horizontal plane
- $\vec{azp}$  is the normal vector of the azimuth plane

Analogous definitions apply for the elevation.

The strategy is to find the vector perpendicular to the plane and a point in the plane (station position) to build the plane equation. To do so, the vector included in the plane needs to be calculated:

$$\vec{az} = \cos(az) \cdot \vec{n} + \sin(az) \cdot \vec{e}$$

Together with another vector in the plane (the vertical vector):

$$\vec{azp} = \vec{az} \times \vec{u}$$

The azimuth plane equation is therefore:



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$$\overrightarrow{azp} \cdot \begin{pmatrix} x_u - X_S \\ y_u - Y_S \\ z_u - Z_S \end{pmatrix} = 0$$

Where  $\overrightarrow{P_S} = (X_S, Y_S, Z_S)$  is the station position.

The same strategy applies for the elevation angle:

$$\overrightarrow{el} = \cos(el) \cdot \overrightarrow{az} + \sin(el) \cdot \frac{\vec{u}}{|\vec{u}|}$$

$$\overrightarrow{elp} = \overrightarrow{el} \times \overrightarrow{azp}$$

$$\overrightarrow{elp} \cdot \begin{pmatrix} x_u - X_S \\ y_u - Y_S \\ z_u - Z_S \end{pmatrix} = 0$$

#### 4.2.1.2 Mixed solution

If the linearized equation for the satellites is changed so that the variable is the user position and not anymore the delta between the assumed position and the true one, one gets the following expression:

$$\rho_i = \hat{\rho}_i - \frac{(x_i - \hat{x}_u)}{\hat{r}_i} (x_u - \hat{x}_u) - \frac{(y_i - \hat{y}_u)}{\hat{r}_i} (y_u - \hat{y}_u) - \frac{(z_i - \hat{z}_u)}{\hat{r}_i} (z_u - \hat{z}_u) + c \cdot t_u$$

It can be reformulated as:

$$\begin{aligned} & \frac{(x_i - \hat{x}_u)}{\hat{r}_i} x_u + \frac{(y_i - \hat{y}_u)}{\hat{r}_i} y_u + \frac{(z_i - \hat{z}_u)}{\hat{r}_i} z_u + c \cdot t_u \\ &= \hat{\rho}_i - \rho_i + \frac{(x_i - \hat{x}_u)\hat{x}_u}{\hat{r}_i} + \frac{(y_i - \hat{y}_u)\hat{y}_u}{\hat{r}_i} + \frac{(z_i - \hat{z}_u)\hat{z}_u}{\hat{r}_i} \end{aligned}$$

The 5G equations can be expressed in this way

$$azp_x x_u + azp_y y_u + azp_z z_u + 0 \cdot t_u = azp_x X_S + azp_y Y_S + azp_z Z_S$$

Finally, with 2 satellite equations, the system to solve would be:



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$$\begin{pmatrix} \frac{(x_i - \widehat{x}_u)}{\widehat{r}_i} & \frac{(y_i - \widehat{y}_u)}{\widehat{r}_i} & \frac{(z_i - \widehat{z}_u)}{\widehat{r}_i} & c \\ \frac{(x_j - \widehat{x}_u)}{\widehat{r}_j} & \frac{(y_j - \widehat{y}_u)}{\widehat{r}_j} & \frac{(z_j - \widehat{z}_u)}{\widehat{r}_j} & c \\ \text{azp}_x & \text{azp}_y & \text{azp}_z & 0 \\ \text{elp}_x & \text{elp}_y & \text{elp}_z & 0 \end{pmatrix} \cdot \begin{pmatrix} x_u \\ y_u \\ z_u \\ t_u \end{pmatrix} = \begin{pmatrix} \widehat{\rho}_i - \rho_i + \frac{(x_i - \widehat{x}_u)\widehat{x}_u}{\widehat{r}_i} + \frac{(y_i - \widehat{y}_u)\widehat{y}_u}{\widehat{r}_i} + \frac{(z_i - \widehat{z}_u)\widehat{z}_u}{\widehat{r}_i} \\ \widehat{\rho}_j - \rho_j + \frac{(x_j - \widehat{x}_u)\widehat{x}_u}{\widehat{r}_j} + \frac{(y_j - \widehat{y}_u)\widehat{y}_u}{\widehat{r}_j} + \frac{(z_j - \widehat{z}_u)\widehat{z}_u}{\widehat{r}_j} \\ \text{azp}_x X_s + \text{azp}_y Y_s + \text{azp}_z Z_s \\ \text{elp}_x X_s + \text{elp}_y Y_s + \text{elp}_z Z_s \end{pmatrix}$$

#### 4.2.1 Residual calculation

The residual calculation for this algorithm will be used to sort out the solutions that may contain a multipath. The hypothesis of the algorithm is that the 5G technology is not affected by multipath. The residual calculated here is the distance between the computed calculation and the plane provided by the 5G algorithm.

If the equation of a plane is:

$$ax + by + cz + d = 0$$

Then:  $(a, b, c)$  is the vector normal to the plane. We consider that its modulus is 1.

The point to be considered is:  $(x_u, y_u, z_u)$

Then  $(x, y, z) = (x_u, y_u, z_u) + \lambda(a, b, c)$  is the equation of the line that passes through the point and that is perpendicular to the plane. Together with the position of the plane:

$$a(x_u + \lambda a) + b(y_u + \lambda b) + c(z_u + \lambda c) + d = 0$$

Then the residual  $\lambda$  is the distance between the point and the plane:

$$\lambda = abs\left(\frac{d + ax_u + by_u + cz_u}{a^2 + b^2 + c^2}\right)$$

#### 4.2.2 KPI calculation

The KPI (key performance indicator) that will be used is the DOP (dilution of precision) of the computed solution. This term is generally used in the GNSS to account both for the accuracy of the satellite to receiver distance computation and the geometry of the satellites.

The equation used to compute the position is:



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$$\begin{pmatrix} \frac{(x_i - \widehat{x}_u)}{\widehat{r}_i} & \frac{(y_i - \widehat{y}_u)}{\widehat{r}_i} & \frac{(z_i - \widehat{z}_u)}{\widehat{r}_i} & c \\ \frac{(x_j - \widehat{x}_u)}{\widehat{r}_j} & \frac{(y_j - \widehat{y}_u)}{\widehat{r}_j} & \frac{(z_j - \widehat{z}_u)}{\widehat{r}_j} & c \\ \text{azp}_x & \text{azp}_y & \text{azp}_z & 0 \\ \text{elp}_x & \text{elp}_y & \text{elp}_z & 0 \end{pmatrix} \cdot \begin{pmatrix} x_u \\ y_u \\ z_u \\ t_u \end{pmatrix} = \begin{pmatrix} \widehat{\rho}_i - \rho_i + \frac{(x_i - \widehat{x}_u)\widehat{x}_u}{\widehat{r}_i} + \frac{(y_i - \widehat{y}_u)\widehat{y}_u}{\widehat{r}_i} + \frac{(z_i - \widehat{z}_u)\widehat{z}_u}{\widehat{r}_i} \\ \widehat{\rho}_j - \rho_j + \frac{(x_j - \widehat{x}_u)\widehat{x}_u}{\widehat{r}_j} + \frac{(y_j - \widehat{y}_u)\widehat{y}_u}{\widehat{r}_j} + \frac{(z_j - \widehat{z}_u)\widehat{z}_u}{\widehat{r}_j} \\ \text{azp}_x X_s + \text{azp}_y Y_s + \text{azp}_z Z_s \\ \text{elp}_x X_s + \text{elp}_y Y_s + \text{elp}_z Z_s \end{pmatrix}$$

Making a change of variables...

$$x_u = \widehat{x}_u + \Delta x_u$$

$$y_u = \widehat{y}_u + \Delta y_u$$

$$z_u = \widehat{z}_u + \Delta z_u$$

$$t_u = \widehat{t}_u + \Delta t_u$$

...the equation can be written as:

$$\begin{pmatrix} \frac{(x_i - \widehat{x}_u)}{\widehat{r}_i} & \frac{(y_i - \widehat{y}_u)}{\widehat{r}_i} & \frac{(z_i - \widehat{z}_u)}{\widehat{r}_i} & c \\ \frac{(x_j - \widehat{x}_u)}{\widehat{r}_j} & \frac{(y_j - \widehat{y}_u)}{\widehat{r}_j} & \frac{(z_j - \widehat{z}_u)}{\widehat{r}_j} & c \\ \text{azp}_x & \text{azp}_y & \text{azp}_z & 0 \\ \text{elp}_x & \text{elp}_y & \text{elp}_z & 0 \end{pmatrix} \cdot \begin{pmatrix} \Delta x_u \\ \Delta y_u \\ \Delta z_u \\ \Delta t_u \end{pmatrix} = \begin{pmatrix} \widehat{\rho}_i - \rho_i \\ \widehat{\rho}_j - \rho_j \\ \text{azp}_x X_s + \text{azp}_y Y_s + \text{azp}_z Z_s - \text{azp}_x \widehat{x}_u - \text{azp}_y \widehat{y}_u - \text{azp}_z \widehat{z}_u \\ \text{elp}_x X_s + \text{elp}_y Y_s + \text{elp}_z Z_s - \text{elp}_x \widehat{x}_u - \text{elp}_y \widehat{y}_u - \text{elp}_z \widehat{z}_u \end{pmatrix}$$

Or in a matrix form:  $H \cdot \Delta x = \Delta \rho$

Note that  $\Delta \rho$  is a notation taken from the GNSS domain, but for the 5G equations, it represents the distance between the position and the plane.

Then the new position vector is:

$$\Delta x = H^{-1} \cdot \Delta \rho$$

The associated covariance matrix is:

$$(\sigma H^T \cdot \sigma H)^{-1}$$



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Usually, the variance  $\sigma^2$  is the  $\sigma_{UERE}^2$  but in this case, one has to account for the 5G equations which will not have the same variance.  $\sigma_{UERE}^2$  is the variance of the User Equivalent Range Error, or in other words the variance of the error made in the calculation of the pseudo-range. For the 5G positioning equations, it will be necessary to change that error variance.

Therefore,

$$H \cdot \sigma = \begin{pmatrix} \frac{(x_i - \hat{x}_u)}{\hat{r}_i} \sigma_{UERE} & \frac{(y_i - \hat{y}_u)}{\hat{r}_i} \sigma_{UERE} & \frac{(z_i - \hat{z}_u)}{\hat{r}_i} \sigma_{UERE} & c \cdot \sigma_{UERE} \\ \frac{(x_j - \hat{x}_u)}{\hat{r}_j} \sigma_{UERE} & \frac{(y_j - \hat{y}_u)}{\hat{r}_j} \sigma_{UERE} & \frac{(z_j - \hat{z}_u)}{\hat{r}_j} \sigma_{UERE} & c \cdot \sigma_{UERE} \\ azp_x \cdot \sigma_{5G} & azp_y \cdot \sigma_{5G} & azp_z \cdot \sigma_{5G} & 0 \\ elp_x \cdot \sigma_{5G} & elp_y \cdot \sigma_{5G} & elp_z \cdot \sigma_{5G} & 0 \end{pmatrix}$$

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-  
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## 5 Test bed

### 5.1 Architecture

#### 5.1.1 Overview

The preliminary architecture of the test bed is presented in the figure below and will be refined for the next release of the document.

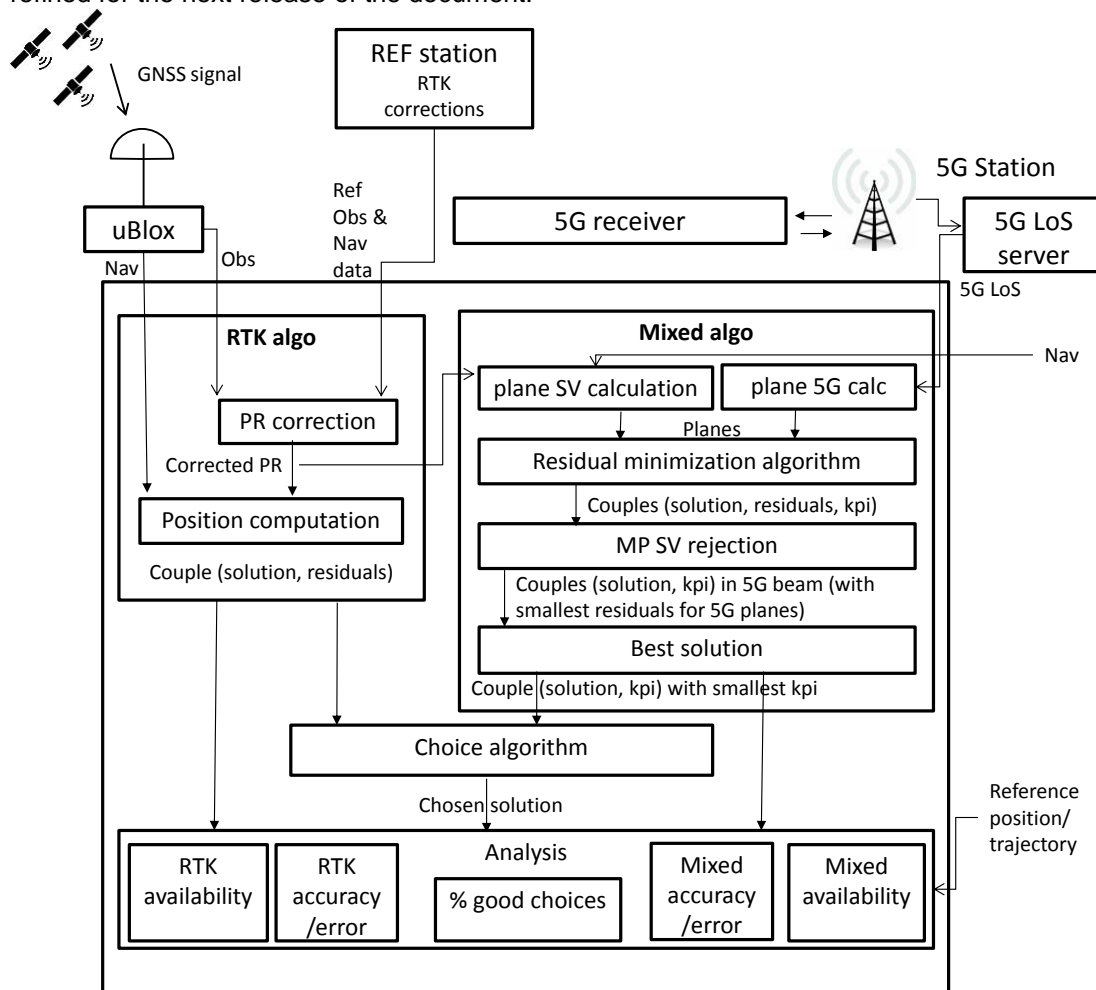


Figure 25: Test bed architecture

#### 5.1.2 GNSS subsystem

The GNSS subsystem of the test bed will:

- compute the position with the RTK method exposed above (independently from the mmWave subsystem)



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- send the computed satellite pseudoranges to the mixed algorithm for combined GNSS/mmWave positioning

It is composed of a GNSS receiver, a reference station, and a laptop running the RTK algorithm.

#### 5.1.2.1 GNSS receiver

The GNSS receiver shall be capable of processing the signals from the new Galileo constellation. Mass-market receivers are not yet compatible with Galileo: the new evaluation kit from ublox will be used instead (EVK-M8T model, see Figure 26 below), which allows to record raw measurements from Galileo, GPS and GLONASS for post processing. In order to fit the most to the capabilities of current smartphones, the receiver will be single-frequency only, and a simple antenna patch will be connected to it. Dual-frequency receivers are preferable because they can remove errors due to ionosphere delays, but these errors are also removed with the RTK method (see §2.2.2) and without using a costly receiver.



Figure 26: GNSS receiver

#### 5.1.2.2 Reference station

*The reference station required for the RTK technique will be the OUL200FIN station from the EUREF Permanent GNSS Network.*

It is located 20 km away from the university of Oulu where the tests will be conducted, which is an acceptable distance for the RTK technique.



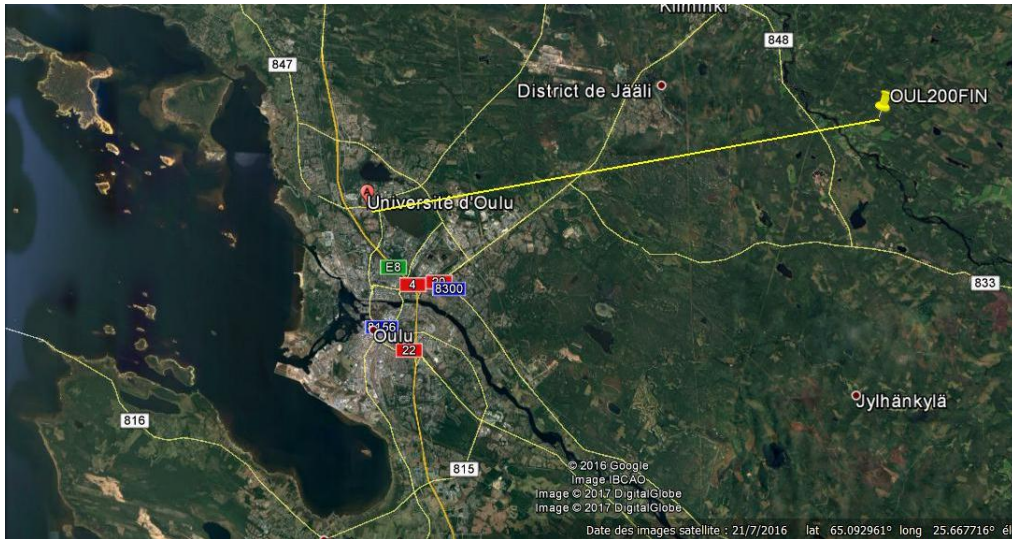
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**Figure 27: Baseline from reference station and the university of Oulu**

The reference station collects GNSS signals from GPS, Galileo and GLONASS constellations. All the data are stored in files on an online server. The one that will be used for RTK positioning are called “highrate” and contain code and carrier measurements recorded at every second.



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**Figure 28: Oulu reference station picture**

If this reference station is not available, as a backup, another u-blox receiver could be used instead and installed a few hundreds of meters away from the University of Oulu at a well-known location.

### 5.1.2.3 Laptop

A laptop will be used for the position computation to simulate a 5G mobile terminal. It will:

- Collect and store raw measurements from the GNSS receiver with a software from u-blox called *u-center* (see Figure 29)
- Collect “highrate” files from the reference station
- Compute the position using the RTK method with a software called *rtklib*, which allows a precise analysis of the positioning solution (see Figure 30)
- Send GNSS data to the mixed algorithm

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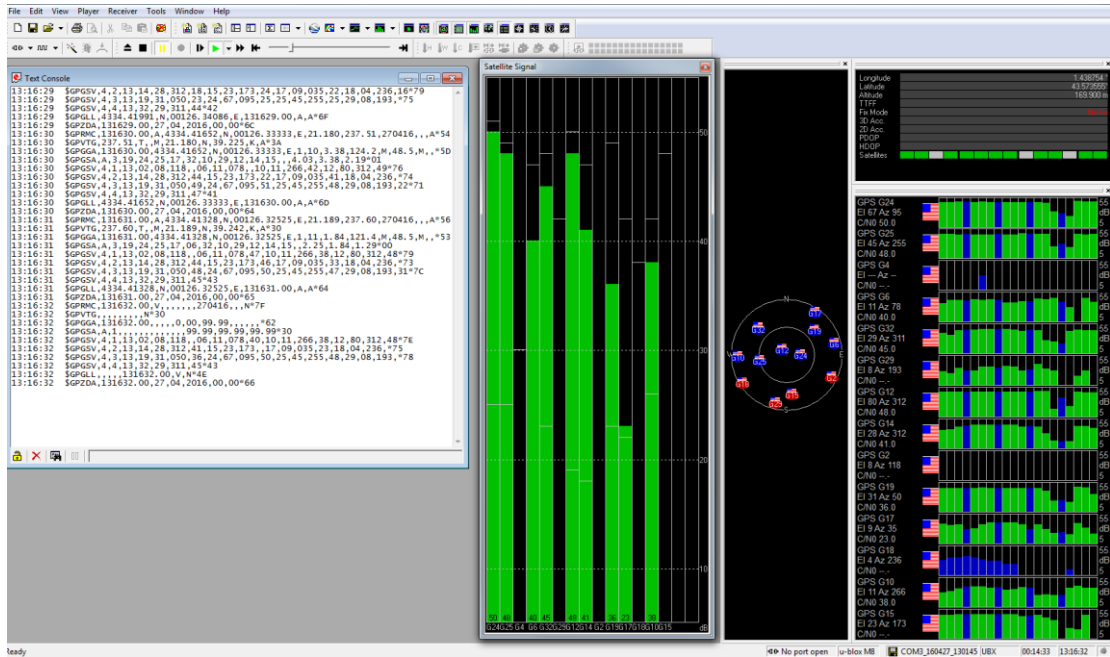


Figure 29: u-center interface

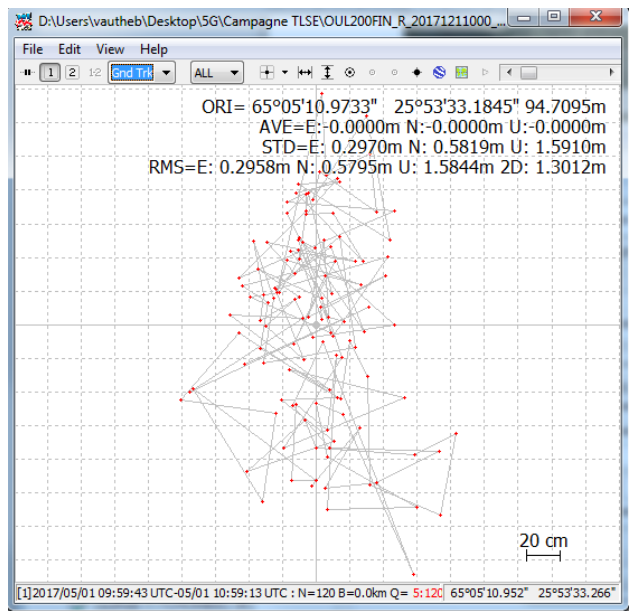


Figure 30: rtklib interface

The laptop is thus the centralisation point for GNSS measurements, with the following interfaces:

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- USB with the GNSS receiver
- Ethernet/Wifi with the reference station database. This simulates the future 5G connection that will be available to the user in the coming years.
- Software only with the mixed algorithm, which is also implemented in the laptop.

### 5.1.3 mmWave subsystem

The full capabilities of mmWave positioning system will be investigated via computer simulations. The system used to demonstrate the mmWave positioning system consists is mmWave radio unit, and the laptop to run the positioning algorithm. The mmWave radio is same as mmWave backhaul radio unit (BRU) used in the EU side radio access network for 5G radio link. As described in deliverable D2.1 the mmWave system consists:

- mmWave backhaul radio unit (BRU) with support for beamforming. BRU includes mmWave air interface (AI0) and L1/L2 interface (I1) for IP traffic
- multi-RAT radio unit operates as traffic aggregator/multiplexer from the wireless backhaul to other radio technologies.

Further details of the output of the BRU will be defined in (Deliverable [D3.5] at M12 and [D6.1] at M14).

A laptop is interfaced via Ethernet/Wifi to the BRU as well as to the another computer running the mixed algorithm.

## 5.2 Test cases

Three types of environment are considered for reflecting ubiquitous positioning: open sky, semi urban and indoor. The GNSS-only and mixed solutions are intended to be tested in the open sky and semi urban environments, but not in indoor because of the lack of satellite signals in this environment. For the mmWave-only solution currently in development, theoretical results will be presented for all three environments.

Positioning system →	mmWave-only	mmWave+GNSS	GNSS-only
Open sky	Theoretical results	✓	✓
Semi urban	Theoretical results	✓	✓
Indoor	Theoretical results	✗	✗

The tests will be static and conducted in the University of Oulu for practical reasons (5G prototype antennas will be placed here).

The precise location of the tests will be checked out in mid-June in the University of Oulu on the occasion of the project annual review.



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## 5.3 Expected results

### 5.3.1 GNSS positioning

For GNSS positioning, the RTK method has its full potential in a clear-sky environment like rural areas. Indeed, a large number of satellites are available and multipath is rare.

In an urban environment, buildings mask satellites and generate multipath. The position given by GNSS may not be accurate enough: that is why a mixed algorithm combining GNSS and 5G measurements is proposed in section 4.

In indoor environment, the use of a positioning solution based on GNSS is not possible since signals are blocked by the building materials.

### 5.3.2 5G positioning

From the 5g only –case, the main expected results as research outcome will be first, the algorithm design and verification via simulation as well as performance comparison against analytical lower bounds, and second, the comparison of real life measurements of the performance utilizing the PoC platform. The results will be reported on a high quality peer-reviewed conference publications, namely targeting to European Conference on Networks and Communications (EUCNC) and European Signal Processing Conference (Eusipco), In addition to the conference articles, the results are collected and reported on the journal article, .e.g. IEEE Transactions or IEEE Magazine articles.

Outcome targeting to the industrial community, the main expected results is the showcase of the algorithm on a PoC demonstration platform. Namely, a fully functional algorithm accounting the different levels of information available, and functionality referring to the implementation level of the algorithm so that it will interoperate with server running 5G-GNSS mixed algorithm. Thus, it will be possible to verify and compare the results in different real life scenarios.

### 5.3.3 Mixed algorithm

The expected results of the mixed positioning solution are strongly related to the KPI calculated in section §4.2.

It has to be noted that  $\sigma_{5G}$  is a variance that depends on the position. The closer the receiver is to the 5G antenna, the lower the variance. This means that depending on the situation,  $\sigma_{5G}$  can be smaller or greater than  $\sigma_{URE}$ . The expected result is therefore:

- In a urban configuration, where the 5G antennas are close to the user, the positioning thanks to 5G will significantly improve the KPI
- In a country-side environment where antennas are far away and satellites are easily tracked, the best solution shall not include 5G equations
- Somewhere in the middle there shall be an environment where the cooperation between both techniques is possible. The satellites will provide good positioning and the 5G can cut out multipath.



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## 6 Conclusion

This intermediate report has led to the description of the GNSS precise positioning techniques and to the selection of the one which is the most suitable regarding positioning use cases, It has also explained the concept of mmWave positioning and has defined an algorithm mixing information from GNSS and 5G to provide a robust and precise positioning in urban environment. Lastly, it has described a preliminary architecture of the test bed, listed the test cases and the expected results.

All these inputs will be used to develop and implement in the following months the positioning test bed that will be demonstrated in the university of Oulu.

The final version of this document will contain a more detailed description of the test bed and test cases.



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