

TECHNICAL ANALYSIS OF NEW PARADIGMS INCREASING EGNSS ACCURACY AND ROBUSTNESS IN VEHICLES

-
EUROPEAN GNSS AGENCY
MAY 2015

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ACRONYMS

2G	Second Generation Mobile
3G	Third Generation Mobile
4G	Fourth Generation Mobile
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AGNSS	Assisted GNSS
AOA	Angle Of Arrival
ATSC	Advanced Television System Committee
BS	Base Station
CEN	European Committee for Standardization (French: Comité Européen de Normalisation)
CEP	Circular Error Probability
COTS	Commercial-On-The-Shelf
CS	Commercial Service
DR	Dead Reckoning
DSRC	Dedicated Short Range Communication
DT	Digital Tachograph
DTMB	Digital Terrestrial Multimedia Broadcasting
DVB-H	Digital Video Broadcast – Handheld
DVB-T	Digital Video Broadcast – Terrestrial
DVB-T2	Digital Video Broadcast – Second Generation Terrestrial
EC	European Commission
ECEF	Earth-Centred-Earth-Fixed
EDAS	EGNOS Data Access Service
EFC	Electronic Fee Collection
EKF	Extended Kalman Filter
EGNOS	European Geostationary Navigation Overlay System
EGNSS	European GNSS (<i>encompassing Galileo and EGNOS</i>)
ETSI	European Telecommunications Standards Institute
EU	European Union
FP7	Seventh Framework Programme
GBAS	Ground Based Augmentation System
GDOP	Geometric Dilution of Precision
GNSS	Global Navigation Satellite System
GSA	European Global Navigation Satellite Systems Agency
GSM	Global System for Mobile Communications
HMT	Hazardous Material Tracking
ICBM	InterContinental Ballistic Missiles
ICT	Information and Communications Technologies

IGS	International GNSS Service
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
ISDB-T	Integrated Services Digital Broadcasting-Terrestrial
ISO	International Organization for Standardization
ITS	Intelligent Transport Systems
IVS	In-Vehicle System
LAAS	Local Area Augmentation System
LBS	Location Based Service
LC	Loosely Coupled
LCA	Liability Critical Applications
LIDAR	Light Detection and Ranging
LIS	Location Insight Services
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAC	Medium Access Control
MCA	Multi-Criteria Analysis
MEMS	Micro Electro-Mechanical Systems
MFN	Multi-Frequency Network
MM	Map Matching
MPS	Minimum Performance Standard
NCA	Non-Critical Applications
NMA	Navigation Message Authentication
NME	Navigation Message Encryption
OBU	On-Board Unit
OFDM	Orthogonal Frequency Division Multiplexing
OS	Open Service
OTD	Observed Time Difference
OTDOA	Observed Time Difference Of Arrival
PAYD	Pay As You Drive
PND	Personal Navigation Device
PPP	Precise Point Positioning
PPUI	Pay Per Use Insurance
PVT	Position, Velocity, and Time
RFID	Radio Frequency IDentification
RSS	Received Signal Strength
RTK	Real Time Kinematic
RUC	Road User Charging
SBAS	Satellite Based Augmentation System
SCA	Safety Critical Applications
SCE	Spreading Code Encryption
SFN	Single Frequency Network

SNR	Signal-to-Noise Ratio
SoO	Signals of Opportunity
SQM	Signal Quality Monitoring
TC	Tightly Coupled
TDOA	Time Difference Of Arrival
TOA	Time Of Arrival
TRL	Technological Readiness Levels
TTFF	Time To First Fix
TV	Television
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
UTC	Universal Time Coordinated
UWB	Ultra-WideBand
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VHF	Very High Frequency
WAAS	Wide Area Augmentation System
WG	Working Group
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WP	Work Package
WSN	Wireless Sensor Network

1. INTRODUCTION

The scope of the document is

- To provide a short but comprehensive review of the technologies currently in place in the field of EGNSS as applied to the road domain (Section 3), focusing on the stand-alone GNSS receivers, the role of augmentation and aiding systems to GNSS, then complementing with the hybridization with external sources.
- To report on the analysis of the positioning needs for some identified main classes of road applications (Section 4).
- To provide the results of an investigation of the main technological enablers (Section 5), considering potential advance beyond the state-of-the-art.
- To summarise some major outcomes of the analysis (Section 6).

It's worth mentioning that the content of this document doesn't consider in detail the "autonomous vehicle" topic.

1.1. METHODOLOGY

The organisation itself of this document reflects a three-step analysis approach, specifically:

1. Identify the *current technological framework* in the field of EGNSS applied to ITS in the road domain, with the aim to recognize the state-of-the-art from three different perspectives:
 - the stand-alone GNSS receiver, part of the in-vehicle positioning module of a generic positioning system for road applications;
 - the aiding and augmentation data provided by external systems (and received by the GNSS receiver) complementing the information carried over the satellite signals;
 - the integration of GNSS receiver with other in-vehicle technologies, e.g. inertial sensors.
2. Identify the *positioning needs* of the major classes of road applications.
3. Investigate the *potentiality of some technologies* (beyond the state-of-the-art) in effectively enabling the expected positioning performance.

2. EXECUTIVE SUMMARY

The road sector is a major potential market for GNSS applications and satellite navigation receivers are now commonly installed in new cars as a key tool for providing new services to the drivers. As a matter of fact, GNSS is the primary source of in-vehicle positioning in road transportation. Most of in-vehicle positioning systems embed mass-market stand-alone GNSS receivers (see Section 3.1), generally processing only GPS civil signals over the L1 band. However, the current trend is to include other constellations (e.g. GLONASS and Galileo) broadcasting signals on the same band, in order to increase positioning availability and accuracy in conditions of limited sky visibility. These GNSS receivers are typically able to accept differential corrections broadcast by Satellite Based Augmentation System (e.g. EGNOS) and they are often enabled for Assisted-GNSS (see Section 3.2). Several error sources still deteriorate the quality of the position and velocity estimates of a GNSS receiver, in particular in an urban scenario (i.e.: multipath, atmospheric effects, poor satellite geometry due to limited sky visibility, shadowing, etc.). To overcome this limitation, data from existing on-board sensors, either motion sensors (e.g., steering encoder, odometer, wheel velocity encoders) or inertial sensors (e.g., accelerometers and gyroscopes), are loosely integrated with GNSS receivers (see Section 3.3).

Nonetheless, the expansion of terrestrial applications and new Location Based Services (LBS) has fostered the design of complex location systems to comply with the increasingly demanding needs of these applications. Such a complexity depends on the type of the target service, ranging from a simple position reporting (e.g. in the case of a low-end asset management) to the provision of a “reliable” data (e.g. authenticated and with a mastered uncertainty) on the vehicle’s trajectory, mainly for liability-critical applications (Section 4).

Starting from this context, we analysed the main GNSS-based applications in the road domain, gathering them in a set of few classes, each of which referring to some key functions (see Section 4.1.1). Then, for each class of applications, we identified the needs in terms of positioning performances (e.g. robustness, increased accuracy, etc., see Section 4.1.2), that have been mapped to specific performance features (in Section 4.2).

Then we selected a number of “technological enablers” beyond the state-of-the-art that potentially could achieve the expected positioning performance identified in Section 4.3. A deep investigation (see Section 5) of all such technologies from different relevant perspectives (technological maturity, complexity, costs, etc.) allowed pointing out the most promising paradigms in order to increase the GNSS accuracy and robustness in future road applications.

The outcomes of the performed analysis (Section 6) show that:

- The implementation of new schemes for fusing data from GNSS and inertial sensors at low level (see Section 5.3.2) represents a cost-effective solution able to support most of the performance features (e.g. accuracy, authentication, integrity). This is especially true if such schemes are complemented with multi-frequency receivers (Section 5.2).
- The precise positioning techniques (i.e. PPP and RTK, see Section 5.6) on top of measurements taken with mass market GNSS receivers come with a quite low TRL today, but the availability of new satellites from new constellations (e.g. Galileo) will encourage the research on this topic, as it will increase the possibility to use carrier phase measurements also in challenging environments like urban.
- When available (e.g. vehicles equipped with a dedicated OBU as for the DSRC), the SoO represent a good solution in complementing EGNSS, mostly for the purposes of position authentication, since they are non-GNSS technologies (see Section 5.5). Their contribution for other features is not yet mature, but DSRC – as soon as some limitations in the quality of measures will be overcome – appears a promising localization technology to look (see Section 5.5.3).
- Current low cost video-cameras provide a very limited added value in terms of performance improvements. On the other hand expensive devices such as LiDAR are

strongly limited due to their constraints in terms of cost (see Section 5.3.1). An effective support to the positioning performance, accuracy at first, is expected from high-end sensors, but comes with medium-high cost. These expensive sensors are typically used in specific demanding applications (e.g. autonomous driving).

3. CURRENT ROLE OF EGNSS IN ROAD DOMAIN

GNSS is the today primary source for vehicles positioning and is currently used for different purposes:

- Navigation, possibly with real-time traffic information (e.g. with a portable navigation devices);
- Real time monitoring for an efficient fleet management, with the final objective of improving the logistic quality of service;
- Supporting measurements to assess off-line the quality of the delivered services. This in turn enables Location Insight Services (LIS) to provide valuable statistic for economic analysis;
- Geo-localization information collected during operations.

Nowadays, different types of positioning sensors can be used to determine the position and velocity of a vehicle. In road transportation, GPS is the primary source of positioning, but other technologies are often used to complement standalone receivers. Indeed, several error sources deteriorate the quality of the position and velocity estimates of a GNSS receiver, in particular in a urban scenario (i.e.: multipath, atmospheric effects, poor satellite geometry due to limited sky visibility, shadowing, etc.), making stand-alone receivers often unsuitable as sole-mean navigation equipment for many applications.

Today, multi-constellation receivers are quickly becoming the state of the art (e.g.: receivers able to process GPS, Galileo and GLONASS signals transmitted over the same frequency, i.e. the L1/E1 band). They are able to process new GNSS signal formats and can be integrated with inertial sensors and odometers to improve positioning performance. These aspects will be briefly presented in this section.

It is worth to point out that the combination of GNSS receivers with video cameras (application rising interests in the context of precise agriculture) is still rather complex, and developed in the frame of research projects [RD01]. Although video cameras are more and more present on board of the vehicles, they are principally intended for the detection of near obstacles (Driver Assistance Systems, DAS, e.g., park assistance, collision avoidance, lane departure warnings, pedestrian protection) and in some case for road sign recognition, but their integration with the positioning system cannot be considered state of the art [RD02][RD03][RD04][RD05][RD06][RD07]. One of the current barriers to the active integration of visual information into the positioning system is the need of augmenting the digital maps with detailed visual information, which would dramatically increase the size of the digital maps and the complexity of the signal processing.

A similar situation holds for the integration between GNSS and radar or Light Detection and Ranging (LiDAR) measurements [RD08]: although the use of LiDAR can be used to precisely detect obstacles along the road, and its integration with the GNSS receiver has been demonstrated to give benefits, the application is still limited to proof of concepts (e.g., prototyping and demonstration of autonomous vehicles [RD09]), mainly due to the associated cost of the LiDAR equipment [RD07].

In what follows we present a short review of the technology currently in place in the field of EGNSS applied to ITS in the road domain. We develop the analysis starting from the stand-alone GNSS receivers, then we move to consider aiding and augmentation systems, which complement the data from the satellite constellation with other information generated by external systems. We conclude with discussing the current level of integration of the commercial EGNSS receivers for vehicular use with other technologies on board of the vehicles, in particular motion sensors and low-cost Inertial Measurement Units (IMUs).

3.1. STAND-ALONE GNSS RECEIVERS

Today, most of positioning systems for road applications embed mass-market GNSS receivers. Generally, they are single frequency and process GPS signals over the L1 band (i.e.: 1575.42 MHz). They work standalone or are loosely coupled with other on-board sensors. The trend for this type of receivers is to include other constellations broadcasting signals on the same band, in order to increase positioning availability and accuracy in conditions of limited sky visibility [RD10].

Nowadays about ten manufactures producing GNSS chipsets for mass-market applications are present, while several companies embed these components in GNSS modules to be more easily integrated in final products. Figure 3.1 shows the newest products from the main GNSS mass-market chips manufacturers. They are Qualcomm, Broadcom, Mediatek, u-blox, CSR and STMicroelectronics. Beside these producers it is worth to mention NVS Technologies AG that produces GNSS chipsets and modules that are appreciated for their level of flexibility, at a moderated cost. CSR (SiRF series) and STMicroelectronics (Teseo series) are also well known and used in road and Machine-to-Machine (M2M) applications.

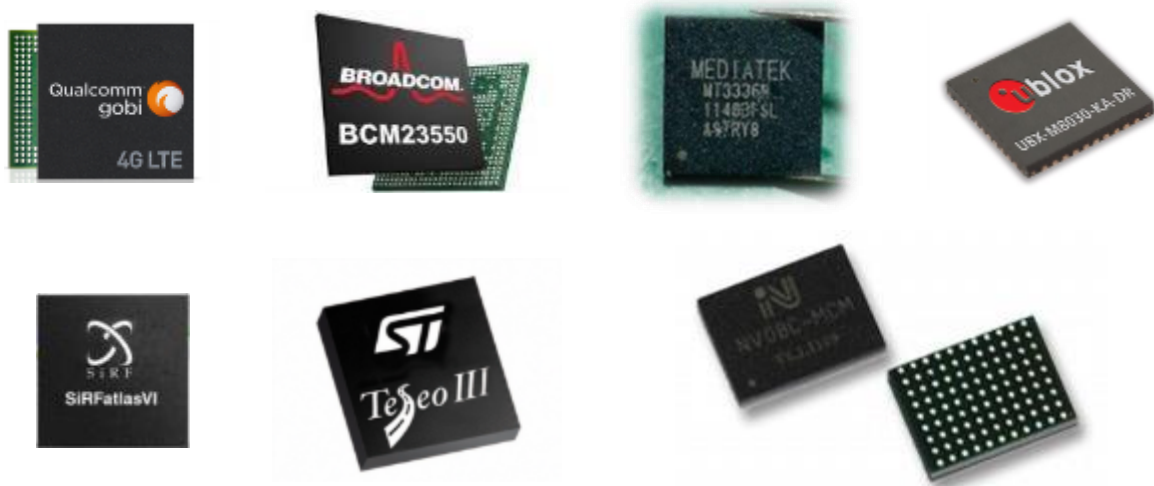


Figure 3.1: Examples of GNSS chipsets produced by different manufacturers (Qualcomm, Broadcom, Mediatek, u-blox, SiRF, STMicroelectronics, and NVS)

In general, the price of these GNSS chips is less than ten EUR, while the price of GNSS modules is between twenty and forty EUR for small quantities. The difference between chips and modules consists in the fact that the first are usually embedded in large production devices (e.g. smart phones) while the seconds are easy to integrate and fit better for small productions with looser size constraints.

Current mass-market receivers are seldom “purely stand-alone” receivers, as they are typically able to accept differential corrections broadcast by Satellite Based Augmentation System (SBAS) over the L1 band (see Section 3.2 Augmentation and aiding systems to EGNSS), often enabled for Assisted-GNSS (A-GNSS) (Section 3.2) and sometimes ready for multi-constellation operations (see Section 3.1.1 Multiconstellation receivers).

Although their nominal accuracy performance are typically below 1.5 m without any external aiding, the actual performance principally depend on the surrounding environment, namely sky visibility, multipath and non-line-of-sight propagation, interference, as well as on the vehicle motion. Actual performance may be dramatically impaired from a harsh environment.

3.1.1. MULTICONSTELLATION RECEIVERS

Multi-constellation receivers address the issue of scarce satellite visibility in urban environments by enabling concurrent access to different GNSS systems. This means that even when the receiver can only see a narrow sky slice, the probability of having enough visible satellites is doubled. In this way, visibility improves since more satellites are likely visible in the non-blocked portions of the sky [RD12].

3.2. AUGMENTATION AND AIDING SYSTEMS TO EGNSS

GNSS augmentation systems were born to continuously provide robust and safe navigation, especially when high precision or enhanced coverage or availability is required. *Accuracy, availability, integrity, and continuity* are the key performance of any GNSS, so that procedures and external aids to improve them have been developed under the label of the *augmentation systems*. Augmentation systems attempts to correct for many of the dominant error sources in GNSS. It is basically accomplished by applying several types of corrections to the user's receiver in order to improve its performance. These corrections are typically computed by a reference station at a precisely known location (or by multiple connected reference stations). Augmentation works only against common mode, spatially correlated errors such as the ionosphere and troposphere delays. Multipath induced errors, as well as interference-induced ones, are not common to the reference station and the user; therefore they cannot be recovered by means of any augmentation system [RD13].

Current mass-market GNSS receivers are typically able to accept differential corrections broadcast by **Satellite Based Augmentation System (SBAS)** over the L1 band [RD14] (e.g., from EGNOS or WAAS), while the commercial (i.e., not open-access) augmentation systems like Omnistar, Starfire, Veripos, Seastar require a receiver setup which is still limited to specific professional applications with high precision requirements and the availability to sustain a subscription fee [RD15].

According to the authors experience gained through practical tests, EGNOS corrections applied to mass-market GPS receivers bring to an improvement equal to 30% on the positioning accuracy, assuming open sky conditions. However, as demonstrated by some measurement campaigns, the applicability of EGNOS corrections and integrity information shows some limitations in vehicular scenarios, especially in urban canyons [RD16]. It must be noticed that the availability of EGNOS messages from an alternative source, as the EGNOS Data Access Service (EDAS), can potentially reduce this problem [RD17].

Another widely adopted technology in GNSS mass-market receivers, especially embedded in smartphones and car navigators, is the **Assisted-GNSS (AGNSS)** [RD18]. It is well known that most of today's LBS use GPS receivers that, considering the present performance of Component Off The Shelf (COTS) devices, normally take around 30 sec to fix the user's location, because they need to download ephemeris and almanac information from the satellites (in cold start conditions). However, under critical signal in space conditioning, the receiver could take minutes to provide useful and reliable information. This is, of course, a very limiting factor for LBS that in most cases need a response time of around a few seconds. AGNSS techniques (especially Assisted-GPS – AGPS) have been designed in past years for two main purposes: to reduce the Time To First Fix (TTFF) and to increase the sensitivity of the receiver in harsh environments (e.g., indoors and urban canyons). The core idea is to provide assistance data to the terminal via a wireless network. Such aids include but are not limited to [RD19]:

- Precise ephemeris, and so the precise position of satellites;

- Constellation almanac;
- Reference position (of the terminal) and reference time;
- Ionospheric corrections;
- Acquisition parameters (estimated Doppler shift).

A positioning server at the network level is in charge of generating assistance data (aiding information), but normally it can also compute the user position on the basis of the observables sent by the user to the server. It is, in fact, possible that the positioning server can be connected to augmentation systems, such as local differential correction networks, as well as wide area GNSS augmentation systems (e.g. EGNOS/EDAS), providing increased accuracy. The communication between the terminal and the positioning server can be set up using two approaches:

- *Control-plane*, in which assistance data are sent via pre-defined cellular network signal structures (e.g. 3G, 4G);
- *User-plane*, in which assistance data are sent via a general TCP/IP data connection, thus not requiring any wireless standard specific messages.

Solutions for the user-plane A-GNSS approaches have been developed and standardized by the Open Mobile Alliance [RD20]. Note that the user-plane approach allows, in principle, the creation of a local assistance infrastructure, using, for example, a wireless ad hoc/sensor network having a positioning server available at the network management level. This approach can be employed in peer-to-peer relative positioning, where sensors are distributing external navigation augmentations among them.

In the last decade, cellular network standard protocols have allocated resources to carry GNSS assistance data to GNSS-enabled mobile devices, in order to implement AGPS/AGNSS services in both Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) networks. 3GPP boosted location services in Long-Term Evolution (LTE) release 9, frozen in December 2009 [RD21].

Due to their wide adoption in commercial devices, **SBAS** and **AGNSS** can be considered as **consolidated technologies in the state-of-the-art for mass-market applications**, thus they will not be further discussed in this document.

3.3. HYBRIDIZATION WITH EXTERNAL SOURCES

Broadly speaking, the information provided by the aiding and augmentation systems discussed above is intended to improve the quality of the received signal (thanks to the signal corrections given by the augmentation systems) or to facilitate the receivers' signal processing (thanks to the assistance messages provided by the aiding systems); however, this additional information intrinsically refers to the GNSS signal-in-space, but does not contain any direct clue related to the position or motion of the platform (e.g., the vehicle) on which the receiver is mounted.

On the other hand, it is common to extract information about the (relative) motion of a vehicle from several on-board sensors, either motion sensors (e.g., steering encoder, odometer, wheel velocity encoders) or inertial sensors (e.g., accelerometers and gyroscopes).

In this section we briefly review the currently employed approaches to integrate the information provided by such external on-board sensors within the GNSS positioning functionality of the receiver. The use of map matching algorithms is also cited as a common method to improve the perception of accuracy of personal navigation devices.

A comprehensive treatment of the on-board technologies used for GNSS-based ground vehicles guidance and control is given in [RD07].

3.3.1. INTEGRATION WITH INERTIAL SENSORS

An Inertial Measurement Unit (IMU) is able to provide high data rate of acceleration and rotation estimates of the inertial sensor. Since the sensor is rigidly mounted on-board of the vehicle in a known and calibrated position with respect to the vehicle centre of mass, the inertial information can be used, as an example, for dead-reckoning.

An Inertial Navigation System (INS) output is computed using the data provided by the inertial sensors (*mechanization*). The INS provides a high-rate navigation solution (typically 100 Hz), which is limited by the choice of the computational approach and equipment. Since such position solution only depends on the measurements of the IMU, it is intrinsically immune to external radio interferences.

Unfortunately, measurements taken from inertial sensors exhibit a noise relatively low from second to second, but this tends to drift over time due to the inherent error of the inertial sensors. Since the mechanization process computes body's displacements and velocities by integrating over time the inertial measurements (namely, acceleration and rotation angles), any measurement error is integrated over time, and it is reflected in an unbounded position and velocity error in the long-term.

It is common to categorize IMUs on the basis of their accuracy and price. Table 3.1 illustrates the characteristics of different grades of IMUs, giving the order of magnitude of the biases they are affected, their price segment and some typical applications in which they are employed [RD22]. The segment of interest for this study is clearly the automotive sector (last column in Table 3.1).

As evident from the table, the positional error (drift) of an IMU for automotive applications, with a cost up to 1000 USD, is high (more than 70 km/h). Leveraging on the progress in the field of sensors technology, low cost Micro Electro-Mechanical Systems (MEMS) are now the reference for applications where requirements in term of package dimensions and costs are stringent. For example, MEMS are now integrated in smart phones and embedded systems for mobile platforms and are available for less than 100 USD.

GRADE FEATURE	Navigation	Tactical	Automotive
POSITIONAL ERROR	1-4 km/h	20-40 km/h	20-40 m/s (72-144 km/h)
ACCELEROMETER BIAS [μ g]	50-500	500-1000	> 1200
GYRO BIAS [$^{\circ}$ /h]	0.005-0.01	0.1-10	> 100
PRICE [kUSD]	50-200	10-50	< 1
APPLICATIONS	General navigation applications, high accuracy georeferencing	Short time applications	Short time applications

Table 3.1: IMUs classification.

Opposite to inertial measurements, GNSS measurements are relatively noisy from second to second, but their biases are bounded, so the GNSS positioning does not exhibit long-term drifts. Thus, GNSS provide position and velocity estimation with bounded estimation errors. Nonetheless, this information has a low rate (typically between 1 Hz or 10 Hz) and is susceptible to jamming, blockage, interference and any impairment on the RF signal.

Basically, GNSS and inertial measurements are complementary for two reasons: the characteristics of their errors are different and these are measurements of different quantities. In the last decades the fusion between these two systems has been implemented in many navigation applications because it provides better performance than their standalone operation, which is a consequence of its complementary nature.

The GNSS/INS fusion seeks to take advantage of the synergy as described below:

1. the INS provides navigation information when the GNSS signal is not available;
2. GNSS can be used to correct the INS estimates by an integrated navigation filter that combines inertial system and GNSS measurements;
3. the GNSS/INS integration exceeds the accuracy of the GNSS alone. This is more apparent in scenarios where the GNSS is affected by multipath and non-line-of-sight propagation;
4. the hybridization with an INS provides a navigation solution at a rate much higher than typical GNSS receivers.

Four different categories of integration approaches are usually adopted:

- un-coupled;
- Loosely Coupled (LC);
- Tightly Coupled (TC);
- Ultra-Tightly Coupled.

The first method (un-coupled) is the simplest integration of GNSS and INS. The two systems operate independently, but as soon as a GNSS position and velocity measurement is available, the INS mechanization is reset, so as to get rid of the accumulated biases [RD23]. This method does not provide any performance enhancement with respect to the stand-alone GNSS accuracy; nonetheless it improves positioning availability in case of GNSS outage and increase the rate at which a fresh position and velocity estimate is generated.

The second approach (LC) can be considered the state of the art in automotive applications. The *position and velocity measurements* from both systems are integrated in a Kalman filter that models INS error dynamics and creates a third blended navigation solution [RD24]. Today all the Commercial-On-The-Shelf (COTS) low-cost INSs that already provide a hybrid position by fusing GNSS and IMU measurements (e.g., XSense, MicroStrain) follow a loosely-coupled approach.

The TC technique uses *estimates of pseudoranges and Doppler frequency* extracted from the GNSS receiver and predicted on the basis of the inertial estimates as measurements within an blending Kalman filter. The main advantage of a TC system is in its ability to use even a single GNSS range measurement to aid the position computation [RD24]. Therefore, the TC makes the navigation more robust and is particularly suitable in scenarios where the reception of satellites signals is critical, like urban canyons. **The TC approach is not yet state of the art, but the interest for this type of integration is growing in road applications** where it is possible to include MEMS in the navigation system.

In the Ultra-Tightly Coupled approach, integration occurs at the GNSS tracking loops which are controlled by the blended navigation filter: the position, velocity and time outputs from the navigation processor are projected onto the satellites-to-receiver line-of-sight directions and are used to control the tracking loops of code and carrier for each satellite channel inside the core receiver processing unit [RD25]. The Ultra-Tightly Coupled technique further increases the robustness of the TC integration and is suitable for high dynamic applications. The data fusion is computed at the level of the receiver's core tracking loops, therefore it requires a specific signal processing architecture which differs from those implemented in commercial receivers. The GNSS receiver in this case is no longer an independent navigator since its operation is also partly dependent on INS information. The potential benefits of such an integration are achieved at the expense of a significant increase in design complexity, computational load, and tight time synchronization [RD26].

Furthermore, the stability of the solution is highly dependent on the quality of the IMU sensors so that the effectiveness of the approach is questionable for INS of grade lower than tactical. For these reasons, the Ultra-Tightly Coupled approach is well beyond the state of the art for road applications.

3.3.2. DEAD RECKONING

To counteract navigation solution degradation in situations with poor satellite constellation geometry, shadowing, and multipath propagation of satellite signals, advanced in-car navigation systems commonly use complementary navigation methods, relying upon information from motion sensors such as accelerometers, gyroscopes, and odometers.

The process of transforming the measurements from the vehicle-mounted motion sensor into an estimate of the vehicles position and attitude is generally referred to as Dead Reckoning (DR). DR is also called "inertial navigation" if it only involves inertial sensors [RD27].

In Table 3.2 below, the most commonly used sensors, together with the information that they provide, are summarized.

Sensor	Measurement
Steering encoder	Front wheel direction
Odometer	Travelled distance
Velocity encoders	Wheel velocities
Electronic compass	Heading relative magnetic North
Accelerometer (inertial)	Acceleration
Gyroscope (inertial)	Angular rotation

Table 3.2: Sensors commonly used as complement to GNSS receivers for enhancement of in-car navigation systems (from [RD27]).

All the measurements in the table only contain information on the relative movement of the vehicle and no absolute positioning or attitude information. The translation of these sensor measurements into position and attitude estimates will therefore be of an integrative nature, requiring that the initial state of the vehicle is known. Moreover, the information provided by the vehicle-mounted sensor is represented in the vehicle coordinate system; therefore, before the sensor measurements are processed into a position, velocity, and attitude estimate, they must be transformed into a coordinate system where they are more easily interpreted. Since GNSS naturally gives an absolute position in an Earth-Centred-Earth-Fixed (ECEF) reference frame [RD99], it naturally complements DR/inertial navigation with the initial state it needs, when available.

The process of DR (and inertial navigation) can briefly be described as follows [RD27]:

1. The gyroscope, compass, or differences in wheel speed measurements are used to determine the attitude (3-D) or heading (2-D) of the vehicle.
2. Attitude (or heading) information is then used to project the in-vehicle coordinates measured acceleration, velocity, or travelled distance onto the coordinate axes of the preferred navigation coordinates system, e.g., the ECEF coordinate frame.
3. Travelled distance, velocity, or acceleration is then integrated over time to obtain position and velocity estimates in the navigation coordinate frame.

To give an example, Siemens' car navigation system uses a gyroscope and odometer to perform dead reckoning (DR). The trajectory estimated from DR is then projected onto the digital map. If the estimated position is between several roads, several projections are done, and the likelihood of each projection is estimated based on the information from the GPS receiver and the development of the trajectory over time [RD28] [RD27]. Pioneer is another

manufacturer that has presented advanced consumer in-car navigation systems ([RD29], [RD27]), based on both DR and local attributes stored in a digital map database.

To summarize, the properties of DR systems (including inertial systems) are complementary to those of the GNSS. These properties are given as follows [RD27].

1. They are self-contained, i.e., they do not rely on any external source of information that can be disturbed or blocked.
2. The update rate and dynamic bandwidth of the systems are mainly set by the system's computational power and the bandwidth of the sensors.
3. The integrative nature of the systems results in a position error that grows without bound as a function of the operation time or travelled distance.

Contrary to these properties, the GNSS receivers give position and velocity estimates with a bounded error, but at a relatively low rate, and depend on information from an external source that may be disturbed. The complementary features of the two types of systems make their integration favourable and, if properly done, results in navigation systems with higher update rates, accuracy and capability to provide a more continuous navigation solution under various conditions and environments.

Odometers and velocity and steering encoders have proven to be very reliable DR sensors. For movements in a planar environment, they can provide reliable navigation solutions during several minutes of GNSS outages. However, in environments that significantly violate the assumption of a planar environment, accuracy is drastically reduced [RD27] [RD30].

3.3.3. MAP MATCHING

Nowadays a digital map is available to work with GNSS receivers in most applications related to the road domain, and therefore Map Matching (MM) can be seen in a broad sense as another hybridization method of the GNSS positioning with external information sources. Indeed, a map-matching algorithm could be seen as a component to improve the accuracy performance of a navigation system.

MM is aimed at determining the vehicle location on a road given a map and a series of positioning results. During last two decades quite many research papers on MM, from simple search techniques to complicated mathematical methods, appeared in the literature [RD31][RD32]. MM algorithms integrate positioning data with spatial road network data (roadway centrelines) to identify the correct link on which a vehicle is travelling and to determine the location of a vehicle on that link. In short, MM algorithms are used to determine the location of a vehicle on a road segment.

Approaches for MM algorithms can be categorized into four groups: geometric, topological, probabilistic, and other advanced techniques [RD31][RD32].

In MM the geometric and topological algorithms have the basic problem of choosing correct links when facing a junction and with inaccurate GNSS heading information due to the low speed. It is quite common that the vehicle has to decelerate and stop in front of the traffic lights at a street junction. During this waiting time, MM algorithms may give wrong link information due to the IMU drift errors and the inaccurate GNSS heading.

So far the information flow has been "unidirectional", from the position information provided by the positioning engine (i.e., the GNSS receiver, possibly assisted by other information sources) to the MM algorithm, which associates the estimated vehicle position to the likeliest point (under a certain criterion) onto the map. This approach has the potential of increasing the final positioning accuracy perceived by the user and is common to any personal navigation device in the market.

The potentialities of a "bidirectional" information flow between the positioning engine and an enhanced digital map are an open topic of research nowadays and will be discussed in Section 5.7 Advanced digital map matching.

4. POSITIONING PERFORMANCE FEATURES IN ROAD DOMAIN

The expansion of terrestrial applications including LBS and transportation means such as road or train has fostered the design of complex location systems to comply with the needs of these applications. In the frame of the service provision ensured by the application towards a user or an external entity, these location systems are in charge of providing a consolidated information based on the position of one or more mobile platforms.

The complexity of the information reported depends on the type of service targeted. It can range from a simple position reporting in the case of a low end asset management, to the provision of a reliable information (e.g. authenticated and with a mastered uncertainty) on the mobile's trajectory for liability critical services such as road charging or Intelligent Transport System (ITS).

This wide spectrum of required technical features calls for a new and broader concept at location system level taking into account hybrid solutions in which the use of GNSS technologies is complemented with other sensors to improve the robustness and the performance of the solution.

4.1. MAIN GNSS-BASED APPLICATIONS IN ROAD DOMAIN AND THEIR NEEDS

The scope of this section is to identify the main GNSS-based applications in the road domain - relying on both already performed analysis and literature review - and to gather them in a set of few classes, each of which referring to some key functions (Section 4.1.1). Then, for each identified class of applications, the needs for improved positioning performances (e.g. robustness, increased accuracy, etc.) are discussed in Section 4.1.2.

4.1.1. ROAD APPLICATIONS SURVEY

The road sector is a major potential market for GNSS applications and satellite navigation receivers are now commonly installed in new cars as a key tool for providing new services to people on the move. [RD33] states that the number of embedded devices and in-vehicle units is growing, replacing traditional PNDs, and smartphones are more and more used for road navigation purposes. In this scenario, there is also an increasing regulatory pressure for emergency location sharing (e.g., eCall¹) and safety-related applications.

At least six major classes of road applications enabled by satellite navigation can be recognised [RD38]:

- **Road Navigation:** route guidance using satellite navigation ("car navigation") is already a well-established product offered both by car manufacturers and standalone navigation devices. The majority of these systems are based on satellite navigation systems that can be integrated with onboard sensors (i.e., odometer and gyros) to compute optimal routes in real-time also relying on the combination with electronic maps. Advanced Driver Assistance Systems (ADAS) are other examples of system enabling Road Navigation applications, being developed to increase the driver's comfort and safety. ADAS can range from the basic cruise control to the radar-based adaptive cruise control (ACC), from the lane-keeping system to the collision-warning systems;
- **Tolling:** road and urban tolling based on GNSS implies that the position and trajectory of a vehicle is determined using GNSS in order to decide if the vehicle must be charged or not and to compute the charging value. Representative examples of such "location based

¹ According to a new Regulation recently approved by the European Parliament [RD34], all new types of cars and vans will need to have an eCall system from 31 March 2018 onward. Such system is intended to send an emergency call in case of accident, providing the vehicle identity and its GNSS-based location, aiming to shorten the response time for emergency services.

charging” applications are road user charging (RUC) and on-street parking billing. But also pay-per-use insurance (PPUI) – enabling pricing policies based on timing, location and driving behaviour – can be included in this class;

- **Emergency Services:** the use of GNSS for emergency services and incident management can make the response to emergency situations much faster and efficient saving lives. The precise location of vehicle (as for the eCall system) can be sent to rescue authorities and can use the emergency and rescue vehicle fleet management system to assign the most adequate vehicle to respond to the incident;
- **Traffic Management:** the monitoring and management of traffic fluidity will be significantly facilitated when a great number of cars are equipped with satellite navigation receivers and guidance systems (e.g., real-time road and traffic info services aiming, for instance, to anticipate a traffic jam and suggest approaching vehicles to choose different route);
- **Fleet Management and Vehicle Tracking:** GNSS-based fleet management systems are used to locate vehicles (e.g. trucks, buses, police cars, taxis) in order to optimize resource management, reduce travel time, increase security and reduce fuel consumption. As a consequence of this significant growing new ITS services are expected to be deployed in the coming years, taking the use of GNSS far beyond in-vehicle navigation. A quite specific Vehicle Tracking application driven by regulation is the Digital Tachograph (DT), a recorder for professional drivers’ activities aiming to enforce rules on driving times and rest periods, then guaranteeing fair competition and road safety [RD35]. The new EU regulation introduces the use of GNSS positioning in the future DTs, also fostering – according to [RD33] – the use of satellite-based positioning authentication to guarantee the origin and the trustability of the DTs records.

Even if the expected output of a GNSS-based positioning system² is basically the same for all the enabled applications (i.e., the position, the velocity and the time of the road user car), each specific application may ask for specific positioning performances according to the service provided (or improved performance in supporting future evolution). For instance, a reliable and accurate localization is strictly needed for eCall, while an authenticated Position Velocity and Time (PVT) may effectively support the tracking of hazardous material transportation.

Within the framework of one of the most significant running standardization process [RD37], possible GNSS-enabled applications in the road domain have been gathered in a set of different classes (see Table 4.1 below), each referring to some key functions in terms of positioning (e.g. reliability, accuracy).

² According to [RD39], a positioning system is the “set of hardware and software components, which can be in different locations, but interconnected, which contribute to estimating the position, speed and associated timestamp of a mobile”. The terminal component of a positioning system (i.e. the unit carried by the vehicle, typically a GNSS receiver which may also be hybridised or assisted) is referred as “positioning terminal”.

Class	Examples of applications ³	Key functions
Location based charging	Road user charging	- Reliability of the detection of virtual gates crossing
	On street parking billing	- Billing service unavailability
PAYD charging	Pay per use insurance	- Representativity of the computed distance - Representativity of the reported trajectory
Cooperative basic geo-localization reporting	Transport on demand	- Reported position accuracy - Location service availability
	Road and traffic data collection (V2V – V2I technologies)	
Non-cooperative basic geo-localization reporting	Recovery after theft	- Reported position accuracy - Location service availability
	Fleet management	- Service reliability, including spoofing attempts detection
Reliable geo-localization	eCall	- Reported position accuracy - Location service availability - Confidence level associated to the reported parameter
Reliable vehicle movement sensing	Legal speed enforcement	- Movement caption accuracy
	Eco-driving and carbon emission foot-printing	- Confidence level associated to the reported parameter

Table 4.1: List of possible application classes (from [RD37]).

At the end, considering the outcomes above but having in mind the ultimate scope of this survey (i.e., gather the GNSS-based applications in the road domain in a set of few classes, each of which referring to some key function) and also taking into account the GNSS market of today [RD33], for the purposes of this document the following classification is proposed:

³ Another lists of possible applications can be found in a recent EC study [RD36] dealing with the certification of EGNSS-based road transport applications: digital tachograph, eCall, in-vehicle signage, intelligent speed adaptation, limited traffic area monitoring and control (urban), location-based billing, PAYD insurance, regulated fleet management and control (urban), remote vehicle immobilisation, road user charging, wrong way (ghost) driver).

Safety-Critical Applications (SCA)	<p>Applications in which the life of the vehicle's driver directly depends on the performance of the GNSS-based in-vehicle positioning system (e.g. accuracy, availability, integrity).</p> <p><i>All the autonomous driving applications are SCA, but also some advanced Road Navigation aid (e.g., ADAS), the Hazardous Material Tracking, and some Emergency Services.</i></p>
Payment-Critical Applications (PCA)	<p>Applications in which the performance of the GNSS-based in-vehicle positioning system may have economic implications, being the usage of a vehicle (in terms of its position over the time) subject to a payment.</p> <p><i>All location-based charging applications are PCA by definition, e.g. RUC, PAYD, and PPUI.</i></p>
Regulatory-Critical Applications (RCA)	<p>Applications enforced by transport policies induced by national or international legislations, where the use of the GNSS-based positioning is fostered to guarantee the intended requirements.</p> <p><i>Even if potentially eligible as a SCA (being an "emergency services"), the pan-European eCall is actually a regulated applications. The same is for the Digital Tachograph.</i></p>

4.1.2. NEEDS FOR IMPROVING POSITIONING PERFORMANCE

Starting from the survey performed in the previous section and particularly considering the proposed classification, this section deals with the common needs for improved positioning performance for clusters of GNSS-based road applications.

SCA

Road Navigation - enhanced

Autonomous driving

Autonomous vehicles are enabled by the combination of different technologies and sensors, allowing the in-vehicle system to identify the proper actions. GNSS plays a key role in supporting autonomous vehicles by providing relevant inputs for integrated navigation, such as **accurate position** and **speed** of the vehicle. Because the critical implications of any loss of GNSS (even considering the integration of other sensors), the position and speed estimation shall be **highly available**. Moreover, as a common need for all the SCA, the position (and speed, in this case) shall come with a statement/indicator about the **statistical confidence** associated to the estimation process.

Road Navigation – enhanced

ADAS (e.g. “safe” speed advice)

In general terms, ADAS are systems intended to help the vehicle’s drivers in ensuring a safety and better driving. For instance, ADAS may automate lighting, provide adaptive cruise control, automate braking, alert driver to other cars or dangers, keep the driver in the correct lane, or show what is in blind spots. For the purpose of our analysis, only the “safe” speed advice feature is considered here as an example.

With the aim to inform the driver when his/her speed appears to be too high for the road and the traffic or weather conditions, at first the estimated position shall be **accurately** map-matched on the proper road segment (to which all relevant information are associated). A mismatching could result in an erroneous “safe” speed suggestion, possibly leading to accident. In addition, the speed of the vehicle shall be **accurately** estimated as well. Moreover, as a common need for all the SCA, the position (and speed, in this case) shall come with a statement/indicator about the **statistical confidence** associated to the estimation process.

Fleet Management – enhanced

Hazardous Material Tracking

The **position** and the **speed** of the truck transporting the hazardous material shall be quite continuously **available** and **quite accurate** enough to follow the transport along the road network (possibly map-matching each position on a specific road segment). In this scenario, considering the peculiarity of the transported material, the **robustness against any malevolent spoofing attack** shall be ensured.

PCA

Tolling

RUC, on-street parking billing (“location-based charging” in general)

Tolling applications refer to the location-based charging applications, where the virtual gates crossing of a vehicle is detected or the time spent inside a certain perimeter by a vehicle is estimated. Moreover, considering that the commercial transactions are basically based on the position of the vehicle, the **robustness against any malevolent spoofing attack** shall be ensured: in fact, self-spoofing attacks can be put in place to provide false position data in order to pay less.

Pay-per-use services

PAYD, PPUI

Pay-As-You-Drive (PAYD) and Pay-Per-Use-Insurance (PPUI) are the typical applications which charge a user on the basis of the time spent driving across certain extended areas (for example, an insurance fee per hour could be higher if the car is driven across a city area than along rural roads).

For this reason, a correct assessment of the **position authenticity** and the **robustness to interference** are fundamental.

RCA

Emergency Services

eCall

Whatever the trigger for the emergency call (i.e., either automatic by vehicle's sensors in case of an accident or manual by the driver or witnesses in nearby cars), the caller's position provided to the emergency responder shall be **available** (as output of the positioning system in the vehicle) and **accurate**, possibly map-matched on the road. Moreover, the position shall come with a statement/indicator about the **statistical confidence** associated to the position estimation process.

Road Navigation - enhanced

Navigation for emergency vehicles⁴

Even if not a RCA, the navigation aid for the professional vehicles involved in emergency services (triggered by an eCall) is treated here because of its inherent relationship with eCall.

Once the accurate position of the vehicle involved in an accident is available (see Emergency Services above), the emergency services shall be properly guided towards the location of the accident. Here "properly" has to be intended that the positioning system in the emergency vehicle shall be prompt to **accurately** estimate its position (asking for a **reduced time-to-first-fix**) but also **available** along the route. Moreover, the position shall come with a statement/indicator about the **statistical confidence** associated to the estimation process.

Vehicle Tracking

Digital Tachograph

For the purposes of DT, the start and the end position of the any work session shall be automatically recorded (vehicle movement detection is needed, in redundancy with the vehicle's sensors), as well as the time even if without stressed accuracy requirements. New regulations are being issued in Europe in order to increase the reliability and the trustworthiness of the recorder data by mandating the inclusion of GNSS capabilities in future DT devices.

As such, the demand for the **position authenticity**, **robustness to interference**, and **integrity** of the estimated position is clearly posed, as well as for **availability**, whereas the requirement in terms of continuity seems less stringent with respect to SCA applications.

4.2. POSITIONING PERFORMANCE FEATURES

According to [RD39], a "performance feature" is a given characteristic used to qualify and quantify the service provided by a generic system, e.g. horizontal accuracy for a positioning system. Moreover, the definition of the means of measuring a given performance feature of a system represents the "performance metric". An example of metric for the performance feature "accuracy" can be the median value of an error sample acquired during a given test following a given protocol.

Table 4.2 (merging information from [RD38], [RD39], [RD40]) lists a set of possible "performance features", providing a formal and not ambiguous definition for each feature together with a draft consideration on the relevance of each feature for the positioning needs above.

⁴ Even if not a RCA, the navigation aid for the professional vehicles involved in emergency services (triggered by an eCall) is treated here because of its inherent relationship with eCall.

Horizontal position accuracy

Statistical measure of the horizontal position (or velocity) error (e.g. 95th percentiles of the cumulative error distribution), being this error the difference between the true horizontal position and the position (or velocity) estimated by a positioning system at a given time.

The requirements for this feature can range from relaxed constraints for personal navigation applications, to more stringent ones for LCA such as road user charging and tracking of dangerous goods.

Vertical position accuracy

Statistical measure of the vertical position error (e.g. 95th percentiles of the cumulative error distribution), being this error the difference between the true vertical position and the position estimated by a positioning system at a given time.

This feature applies when vertical guidance is required, for instance to allow proper positioning in case of parkade (multi-levels parking) or overlapping road segments, especially in urban environments.

GNSS time accuracy

Statistical measure of the GNSS time error (e.g. 95th percentiles of the cumulative error distribution), being this error the difference between the true GNSS time (as implemented in the GNSS system timing facility) and the time returned by the positioning system based on the PVT solution.

Generally, this feature is of interest for applications requiring synchronisation of assets distributed across wide geographical areas, where GNSS time is used as a reference. Focusing on the road sector, GNSS time accuracy applies for example in case on VANET applications (involving a very large number of distributed nodes) that in future might require the use of synchronous Medium Access Control (MAC) in order to overcome the known scalability issue of the decentralized and asynchronous Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method.

Time-to-first-fix (TTFF)

Time taken by the positioning system to report a PVT solution (fix) starting either from the reception of a specific "start" request, or from another triggering event that switches the positioning system on.

This feature is of particular interest for the navigation support (route guidance) of emergency vehicles, provided that the positioning system in the emergency vehicle has to be prompt to accurately estimate its position.

Position authenticity

Authenticity gives a level of assurance that the data provided by a positioning system has been derived from real signals.

RF spoofing may affect the positioning system resulting in false position data as output of the system itself.

Robustness to interference

Ability of the positioning system to operate under interference conditions and to maintain the applicable positioning service level requirements.

Location Systems might be required to operate in constrained RF environments, in particular in the GNSS frequency bands. Note that interference can be either unintentional or deliberate (e.g. jamming)

Position integrity

General performance feature referring to the trust a user can have in the value of a given PVT provided by a positioning system.

It is relevant to SCA and LCA (e.g. critical navigation, billing) where integrity is important. It is expressed through the computation of a protection level associated to a predetermined integrity risk, as a function of the type end-user application.

GNSS sensitivity

Minimum GNSS signal strength at the antenna, detectable by the receiver (dBW or dBm).

The GNSS sensitivity is a relevant feature in all the applications involving possible urban and light indoor scenarios (especially eCall and emergency services).

Availability

The availability of a navigation system is the percentage of time that the services of the system are usable by the users for navigation purposes. Availability is an indication of the ability of the system to provide usable service within the specified coverage area.

The availability is one of the most important performance features in supporting any safety-critical application, e.g. emergency services.

Continuity

Continuity is defined as the operation given that the service level requirements are provided at the start of the capability of a system to provide a positioning service fulfilling a set of applicable service level requirements, throughout the intended operation.

Table 4.2: Definition of the positioning performance features

According to the analysis of the positioning needs for the identified main classes of road applications (Section 4.1.2), each performance feature above plays a different role in supporting the expected needs. A statement about the relevance – in terms of a simple but effective 3-level scale, i.e. **Low-Medium-High** – of each performance feature for the identified needs can be drafted. Table 4.3 below summarizes this analysis.

		Position ⁵ accuracy	Time ⁶ accuracy	TTFF ⁷	Position ⁸ authenticity	Robustness to ⁹ interference	GNSS ¹⁰ sensitivity	Availability ¹¹	Position ¹¹ integrity	Continuity ¹¹
SCA	Autonomous driving	H	H	M	L	M	L	M	H	H
	Road Navigation – enhanced (ADAS)	M/H	M	M	L	M	L	M	H	H
	Fleet Management – enhanced (HMT)	L/M	M	M	H	H	M	H	H	L/M
PCA	Location-based charging (RUC)	L/M ¹²	L	M	H	H	M	H	H	L
	Pay-As-You-Drive	L	L	L	H	H	M	M	H	L/M
RCA	Emergency Services – eCall	M	L	M/H	L	H	H	H	M	L
	Road Navigation – supporting emergency	M	L	M/H	L	H	H	H	M	L
	Vehicle Tracking – DT	L	L	L	H	H	L/M	M	M/H	L

Table 4.3: Correlation between the application needs, gathered in terms of criticality, and the performance features.

⁵ Roughly speaking, “L” means > 10 meters, while “H” means < 2 meters for the position accuracy feature.

⁶ The time accuracy feature can be approximately mapped as follows: “L” means > 1 s, “M” means 1 ms ÷ 1 s, and “H” means < 1 μs.

⁷ The relevance of the Time To First Fix feature is broadly related to the need for hot/warm/cold start conditions. For this reason it is possible to set “L” > 30 s, “M” < 30 s, and “H” < 1 s.

⁸ As clearly stated in the definitions in Table 4.2, the position authenticity is strictly related to the RF spoofing (that results in counterfeit position data).

⁹ “Robustness” has to be intended here as the capability to ensure a prompt detection of any interference (including jamming) on the GNSS bands.

¹⁰ Aiming to assess the relevance of GNSS sensitivity, the availability of on-board equipment other than GNSS receiver (e.g. radar, cameras and other sensors used in an ADAS) is taken into account, being such redundancy enough to reduce the relevance of GNSS sensitivity. Typical values declared for high-sensitivity receivers are on the order of -160 dBm or better, while medium-sensitivity are on the order of -148 dBm. Lower performances are typically not declared.

¹¹ Availability, position integrity, and continuity features are further discussed in D.3.2 [RD124].

¹² The wide range of location based charging applications (e.g. from the RUC to on-street billing) turns into a quite wide range of positioning accuracy needs. For instance, charging applications in urban scenarios are more demanding than along highways.

4.3. TECHNOLOGICAL ENABLERS

Table 4.4 lists all the identified technological enablers that it is expected to effectively achieve the performance features above (Section 4.2). Each technological enabler is detailed in Section 5.

TECHNOLOGICAL ENABLERS		PERFORMANCE FEATURES								
		Position accuracy	Time accuracy	TTFF	Position authenticity	Robustness to interference	GNSS sensitivity	Availability	Position integrity	Continuity
Multi-frequency receivers	Sect. 5.2	✓	✓		✓	✓			✓	
Combination of GNSS receivers with vision sensors	Sect. 5.3.1	✓						✓		✓
Tight integration with IMU	Sect. 5.3.2	✓			✓	✓		✓	✓	✓
Civilian GNSS signals authentication	Sect. 5.4.2				✓					
GNSS spoofing countermeasures	Sect. 5.4.3				✓					
Integration with SoO – DVB-T	Sect. 5.5.1				✓	✓		✓		
Integration with SoO – Cellular networks	Sect. 5.5.2			✓	✓	✓	✓	✓		
Integration with SoO – DSRC	Sect. 5.5.3	✓			✓			✓		
Precise Positioning – PPP	Sect. 5.6.1	✓	✓						✓	✓
Precise Positioning – RTK	Sect. 5.6.2	✓	✓						✓	✓
Advanced digital map matching	Sect. 5.7	✓							✓	

Table 4.4: Correlation between the performance features and the identified technological enablers.

5. TECHNOLOGIES SURVEY

This section provides an investigation of the main technological enablers identified in Section 4.3, considering potential advance beyond the state-of-the-art. The scope is not to give a detail insight of each technology (additional resources are provided in Section 7), but to focus on the key aspects in supporting the expected positioning performance. Apart from a strict technological perspective, other relevant viewpoints are taken into account when possible, e.g. complexity, maturity, costs.

The goal is to make available a sort of evaluation of the potentiality of the identified technologies.

5.1. EVALUATION CRITERIA

This section provides the criteria used in the following sections for the evaluation of the various technologies identified in Section 4.3. A list of criteria is provided in the table below, where a rank description (nature, range, etc.) is associated to each criterion.

Criteria	Description	Rank (Low, Medium, or High)
Performance		
<i>Refer to the performance features in sect. 4.2.</i>	It should assess the capability of the specific technology to fulfil the expected positioning performance.	L (marginal) to H (significant)
Maturity		
Technological readiness ¹³	It should assess the maturity of the technology at present.	L (concept) to H (prototype)
Time-to-market	It should assess the potential of the vehicle on-board equipment and/or possible system components to be promptly implemented aiming to support the technology.	L (very short) to H (long)
Cost		
Estimated cost in 2015 (current)	It should roughly assess (without numbers) the estimated impact of the technology on the cost of the vehicle on-board equipment and/or possible system components (e.g. deployment of access points, ad-hoc communication networks, and servers), both now and in 2025 respectively.	L (marginal) to H (significant)
Estimated cost in 2025		L (marginal) to H (significant)

¹³ The technological readiness criteria is inspired to the **Technological Readiness Levels** (TRL) as listed in the Annex G of the Horizon 2020 Work Programme 2014–2015 [RD41]. The following qualitative mapping has been considered:

- TRL 1-3 → Low (L)
- TRL 4-6 → Medium (M)
- TRL 7-9 → High (H)

Challenges		
Technological challenges	It should roughly assess possible technological challenges (e.g. GNSS signals not available in indoor scenarios), any barriers/obstacles and any framework conditions (such as the lack of regulations and standards).	L (marginal) to H (significant)
Framework conditions (i.e. regulation and standards)		L (marginal) to H (significant)

5.2. MULTIFREQUENCY RECEIVERS

Today, mass market receivers are able to process GNSS signals from different constellations, over a single frequency band. Performances of a quad-constellation mass market receiver are reported in [RD10], while examples of products can be found in [RD11]. Generally, the mass market class refers to receivers sold to the consumers, produced in high volume and with considerable price pressure. These are thought for mobile phones and tablets as well as for in-car systems and Personal Navigation Devices (PND).

Multi-frequency receivers for mass-market applications are not the state of the art yet. With *multi-frequency* receivers, we intend receivers that, in addition to the L-band from 1560 to 1610 MHz, operate with other navigation signals broadcast in the range from 1170 to 1290 MHz. For instance, GPS L2C and L5 signals, GLONASS L2 and L3 signals and Galileo E5 and E6 signals.

From a technical point of view, the main reason that would induce GNSS engineers to use multiple frequencies also in mass-market receivers is to allow for an autonomous measurement compensation of the ionospheric errors. Over the last years, the importance of adding this capability has been reduced with iono corrections from EGNOS or through terrestrial systems like EDAS, even if this last requires the availability of a communication link. Although in most of road applications working in open sky the need of a dual frequency receiver is not felt stringent (i.e.: the positioning accuracy of EGNOS-enabled receiver is < 2 meters), the use of multiple signals is the first step toward enabling the resolution of the carrier ambiguity and in turn would ease methods for precise positioning. As anticipated by [RD107], this fact is already important for the so called "light professional" market, where the price pressure is much less extreme and users actually want the benefits of multi-frequency. The volumes of this market are tiny compared with consumer markets. Examples of light professional applications are the transportation and tracking of dangerous goods, or the precise positioning of special fleet of vehicles used for road maintenance. These are applications that will also benefit of the Galileo commercial service (i.e.: authenticated signal embedding PPP data) and will likely use dual frequency receivers able to process signal on the E1 and E6 bands [RD69].

The use of an additional frequency in mass-market receivers is not complicated from a technical point of view, but it comes with a cost, which seems currently the only barrier limiting this technology. Despite what one could believe, the major part of the cost is associated to the development process rather than the extra silicon and components needed for the additional signals. Experts agree that a production of many millions of pieces can amortize such cost.

At the time of writing, there is a debate on the use of multi frequency receivers for the next generation of mass market applications. Some think that the market will take the benefits provided by advances in power consumption and will remain single frequency, but multi constellations. Others believe that soon mass market receivers will be able to process the signals on E5/L5, in addition to those in E1/L1.

Observing what has been proposed in the scientific literature over the past two years, it seems that chip manufacturers started the design of flexible front end architectures. These allow for saving the development cost of new multi frequency chains, but preserve the possibility to reuse the same chip for different frequencies. Such flexible architectures can be used interchangeably for two frequencies. So, low cost applications will use just one (e.g.: the GPS L1), whereas more demanding applications will employ two copy of the same RF (e.g.: the first for the GPS L1, the second for the GPS L5) [RD107]. This approach leaves the door open for dual-frequency solutions that in turn will allow full advantage of carrier phase measurements. This is the basis for the application of PPP or RTK into the automotive market for fields such as advanced driver-assistance systems.

5.2.1. TECHNOLOGICAL ISSUES OF MULTIFREQUENCY RECEIVERS

Today low cost receivers for road applications are not multi frequency. The barrier is not due to the level of maturity of the technology, but rather to the high costs associated to new developments, that need very high volumes of productions to be amortized. Dual frequency mass market receivers have been studied and prototyped with promising performance in the last years [RD42], but:

- it is not viable for chip manufactures to make silicon for low-volume combinations, nor to divide the overall market over different chips.
- chip manufactures believe that their single frequency mainstream chips should also support the lower volume options, where the need of multi-frequency is more evident.
- chip manufactures cannot impose silicon area or power consumption penalties on the high-volume customers.
- The design of flexible front ends, that could be reused for different frequency seems an appropriated approach, otherwise the low volume of sales of a dedicated dual-band radio would never repay its development costs.

5.2.2. PERSPECTIVES TOWARD THE ROAD SECTOR

Multifrequency GNSS receivers have the ability to strongly reduce the ionospheric error and provide good performance in terms of position accuracy. However, multifrequency receivers are not yet part of In-Vehicle System (IVS) used in mass-market applications, because their adoption is strongly hindered by the high costs associated to new developments, that need very high volumes of productions to be amortized.

However, some professional applications in the road domain require higher accuracy with respect to single frequency receivers and motivate GNSS receiver manufacturers to offer multi-frequency solutions [RD33], leveraging new constellation and signals.

Criteria	Score	Justification
Performance		
Position accuracy	H	Increased position accuracy due to ability to mitigate the ionospheric error. Measurements performed over different bands enable precise positioning (i.e.: PPP or RTK). Enabling the reception of the Galileo CS over E6 band, then exploiting the high-accuracy service (PPP data transmission).
Time accuracy	H	Increased time accuracy due to ability to mitigate the ionospheric error.
Position authenticity	H	Enabling the reception of the Galileo CS over E6 band, and then exploiting the signal authentication service.
Robustness to interference	H	The frequency diversity is an intrinsic method to mitigate interfering signals
Position integrity	M	In open sky conditions, dual frequency receivers strongly reduce the ionospheric error, which is the most dominant error source. The improved accuracy decreases the probability that the positioning error exceeds the PL. On the other hand, the algorithms combining

		measurements from different frequencies amplify the error due to multipath, that is likely in urban. In this case the performance in terms of position integrity decrease.
Maturity		
Technological readiness	H	Dual band RF receivers for GPS and Galileo have been developed in recent R&D projects (e.g.: [RD42]), showing the maturity of the technology.
Time-to-market	M	Despite the high level of technological readiness, the time to market of new products cannot be considered short, mainly due to the high costs associated to the development of new chipsets
Cost		
Estimated cost in 2015 (current)	H	The costs for the development of new multi-frequency GNSS chipsets are still high and represent the major barrier of this technology
Estimated cost in 2025	M	It is expected that in ten years cost-related constraints will be relaxed. Multi frequency mass market receivers will be the state of the art, at least for some professional applications requiring medium-high performance in terms of positioning accuracy
Challenges		
Technological challenges	L	<p>Architectures for dual frequency mass-market receivers have been developed, validated and presented as prototype. The main barrier for the adoption of multifrequency receivers in road is not of technological nature.</p> <p>The design of flexible and reconfigurable RF front end seems an appropriate approach to match the requirements of professional users and save the cost of new development.</p>

5.3. DEEP INTEGRATION WITH SENSORS

New LBSs in the transportation domain require complex location systems to comply with specific user requirements and needs. Often the requirements in terms of accuracy, integrity and data trustworthiness are stringent and call for a new and broader concept of location systems, that takes into account hybrid solutions in which the use of GNSS is complemented with sensors and other terrestrial technologies to improve performance.

GNSS receivers are today more and more combined with sensors installed on board of vehicles. This section considers the integration with vision sensors and IMUs. The discussion is around the “deep integration”, that is the data fusion between measurements from the GNSS module and sensors at a low level, before the computation of the PVT.

5.3.1. COMBINATION OF GNSS RECEIVERS WITH VISION SENSORS

Many manufacturers have so far developed advanced driver assistance systems (ADAS) based on vision sensors, which detect the presence of specific road features to provide the driver with appropriate alert/information. For example, a lane departure warning (LDW) system alerts the driver when the vehicle has driven outside the lane markings of the current lane of travel. The feature used for vision-based LDW is the painted lane lines.

Most of the LDW systems in production now are solely based on video-cameras [RD07]. Cameras are a very popular type of hardware used today for driver assistance. Their advantage is mainly in the limited cost of the hardware involved: digital cameras have been in production for decades and the cost of these devices is relatively cheap. Also the algorithms used for lane positioning using a camera are well established.

Lane positioning can also be accomplished using a light detection and ranging (LiDAR) scanner. LiDAR measures the range to an object by pulsing a light wave at the object and measuring the time between transmission and reception. The light wave for LiDAR applications is a laser. LiDAR scanners combine the laser with a moving mirror that rotates the laser’s beam. This can provide ranging information in multiple directions, both vertically and horizontally. A LiDAR scanner with reflectivity measurements can be used to search for lane markings. One advantage of using LiDAR is its robustness to varying lighting and weather conditions; unlike a camera, LiDAR scanners work independent of surrounding lighting conditions. However, the largest disadvantage of LiDAR scanners is their cost, which has largely prevented so far implementation of LiDAR-based ADAS systems on civilian vehicles.

Vision-based measurements, as well as radar measurements, used in most of the ADAS are designed to provide information relative to the vehicle’s reference frame or the road-based reference frame. However, recent research works propose the integration of such kind of information in the “navigation filter”, in order to improve the accuracy of the final navigation solution to the lane level [RD07].

Basically, the integration of visual information has been proposed at three stages inside the navigation system of a manned vehicle:

- 1) As an additional measurement in input to the navigation filter stage, to enhance accuracy of the estimated position (additional map info necessary);
- 2) At the inertial navigation system (INS) stage, to enhance the robustness of the INS in GNSS-denied conditions;
- 3) At the pseudorange stage, in order to identify and exclude NLOS measurements before their input to the navigation filter.

These approaches are reviewed in the following subparagraphs.

5.3.1.1. Visual information as an additional measurement in input to the navigation filter stage

To use visual information as an additional measurement in input to the navigation filter stage, it is necessary to express this new information in a reference frame compatible with the other existing measurements inside the navigation filter. Lane position measurements are given in the road-based coordinate frame. The road-based coordinate frame can be approximated with a waypoint-based map, in which the waypoints lie in the centre of the lane that is being mapped; the distance between waypoints depends on the road geometry. Generally speaking, in order to achieve lane-level positioning accuracy, the estimated global position and velocity of the vehicle is reported, through an opportune roto-translation of the coordinate frame, to the road-based reference frame, where the visual measurements of the vehicle's position with respect to the lane centre are available [RD07]. Thus, such measurements can enter in the navigation filter as a measure of the distance of the current vehicle position from the current map waypoint. If the map is sufficiently accurate, then a lane-level positioning accuracy can be achieved. To apply this kind of approaches, the position of the base waypoint of the map in the navigation coordinate frame must be known. Also the rotation matrix from the navigation coordinate frame to the road coordinate frame must be known, namely, the attitude of the road coordinate frame with respect to the navigation coordinate frame must be known. All these elements must be saved in a map database, which must be available to the navigation filter. Waypoint-based maps are available through precise location survey.

5.3.1.2. Visual information at the INS stage

A different approach that exploits the information extracted from an on-board video camera to enhance inertial navigation/dead reckoning in case of GNSS outage, can be found in [RD43]. Here, a low cost video camera, such as one of those currently integrated in most mobile devices, is used to calibrate a MEMS inertial sensor which suffer from significant bias, drifts and noise in the absence of GPS measurements. If using the MEMS IMU alone, the navigation solution will diverge to hundreds of meters within several minutes. In this context, a camera can limit the IMU divergence by tracking the locations of optical features in successive images. In this case no map features are involved. A conceptually similar approach has been developed and implemented in a prototype GNSS/INSS/LiDAR software receiver in [RD44]: when GNSS fails, the navigation uses LiDAR observations to keep controlled the inertial sensor errors. Again, no map information is necessary. However, limitations can be found in the stability of the algorithms that track optical features in very challenging scenarios (for example in a crowded urban road, with cars parked along the sidewalks and unpredictable changes of the street furniture) and in the cost of the LiDAR equipment.

It must be noticed that such a family of approaches, based on complementing inertial navigation with visual measurements in GNSS-denied environments [RD45], has been mainly proposed so far for handheld indoor positioning [RD46][RD47][RD48].

5.3.1.3. Visual information to identify NLOS measurements

A third different way to exploit visual information to enhance positioning performance is based on the idea that the navigation filter performance improves if GNSS pseudoranges generated from non-line-of-sight (NLOS) satellites are excluded from the solution computation: an omnidirectional video camera can easily detect the borderline between the sky and the obstacles such as the buildings, thus enabling the exclusion of satellite signals with NLOS directions of arrival [RD49][RD50]. A non-trivial problem is to robustly detect the borderline between the sky and the obstacles from a coloured image, because detection using

the colour camera is affected by cloud cover, illumination conditions, and weather conditions. Infrared cameras are far less affected by such kind of problems [RD49][RD51].

5.3.1.4. Place recognition through visual information

A further family of approaches is exemplified by the work presented in [RD52]. It is a kind of image-based “fingerprinting” [RD13], in which images taken at various locations in a particular environment are recorded with their photo-taken positions and compiled to form a database. Place-recognition (i.e., “fingerprinting”) is then achieved by associating the real-time image taken from unknown location in the environment with a geo-coded image from the database that has the most similar appearance. Various algorithms are developed to associate images with different perspectives by their content appearance. The major drawbacks of such an approach are the necessity of compiling the geo-located image database, its maintenance along the time, its availability to the positioning device and the demanding computational cost associated to image processing. For these reasons this technology seems unsuitable for the integration with GNSS, while it could have more chance for specific indoor applications.

5.3.1.5. Technological Issues of Combination with vision sensors

The use of on-board visual sensors poses a number of issues, some at sensor level, others at the integration level with GNSS.

At **sensor level**, currently the largest disadvantage of LiDAR-based systems is the cost of the hardware. LiDAR is a relatively new technology with a still limited number of manufacturers. Also, using LiDAR scanners to detect lane marking is a new and quite undeveloped science [RD07].

On the other hand, video cameras are relatively cheap and their employment for lane recognition is well established. However, disadvantages include vulnerability to lighting and weather conditions; for example, at dawn and dusk, when the sun is low in the sky, a camera may be blinded by the sunlight.

Independently from the sensor used, the extraction of visual information can be difficult in urban environments where lane markings are in poor condition or visibility of lane markings (and other optical features) are blocked by surrounding traffic.

When the **integration** of such sensors within the GNSS navigation filter is considered, other issues arise.

- First, a more complex signal processing in the navigation filter is necessary, in order to deal with a type of measurements generated in a different coordinate reference frame. Although this is not considered a technological barrier, the size and complexity, as well as the availability, of the map database could be.
- Second, the use of visual information as an aiding to the INS is in fact complementary to the GNSS and seems to give little advantage when GNSS is present. The trade-off between the cost/complexity of installing an additional visual source and the cost/complexity of a more stable dead-reckoning (including IMU and non-inertial motion sensors as sources) is still an open point.
- Third, in general, the maturity of such integration algorithms seems not achieved yet in non-controlled scenarios (i.e., in more complicated environments than those expected for robotic automation, for example crowded urban roads), since the “availability” and “continuity” of such visual information in different scenarios is not clearly established yet.

5.3.1.6. Perspectives toward the road sector

Today, most of vehicles have low cost visual sensors installed as part of the driver assistance system. Even if in nominal conditions they can enhance the performance of GNSS receivers, system integrators might be discouraged to invest in this type of technology, because low cost visual sensors have performance still dependant to the external environment. Superior grade sensors come with higher costs and their use is motivated only in autonomous driving applications.

Criteria	Score	Justification
Performance		
Position accuracy	H	The achievable accuracy <i>in nominal conditions</i> for the two integration types "Visual information as an additional measurement in input to the navigation filter stage" and "Visual information at the INS stage" is promised to be high (enabling lane-level positioning)
Availability	L	Video-cameras are prone to errors dependent on weather and lightning conditions. The likely high variability of the optical features in non-controlled scenarios may affect the availability and continuity of visual information.
Continuity	L/M	The likely high variability of the optical features in non-controlled scenarios may affect the availability and continuity of visual information. Nonetheless, when visual information is used for aiding INS in the absence of GNSS (in particular in tunnels), it can improve continuity and accuracy
Maturity		
Technological readiness	M (L)	M: Sensor technology is developed, although improvements are expected L: The maturity of the integration algorithms seems not achieved yet in non-controlled scenarios (e.g., crowded urban roads) and needs to be assessed.
Time-to-market	M/H	Mentioned technological issues on the integration between visual sensors and GNSS have to be overcome before the integration with visual sensors entering into the market.
Cost		
Estimated cost in 2015 (current)	H	N.A
Estimated cost in 2025	H	N.A
Challenges		
Technological challenges	M	LiDAR: high cost of the hardware Video-cameras: vulnerability to lighting and weather conditions Difficult extraction of visual information in urban environments (optical features blocked by surrounding traffic) Availability of digital maps with lane-level description Reliability of the visual-based integration algorithms in non-controlled scenarios

A tightly-integrated system uses the *pseudorange* and *pseudorange rate* information extracted from the GNSS receiver to compute the corrections to be applied to the trajectory estimated by the INS device. Pseudoranges and pseudorange rates are also employed to estimate, if necessary, the biases that affect the accelerometers and the gyroscopes (this is particularly important when using low cost devices, such as MEMS). Tight integration is based on the definition of a state-space model of the hybrid system and the application of an

Extended Kalman Filter (EKF) to compute the corrections necessary to refine the INS-based trajectory.

It is worth noticing that, in the tight integration case, the GNSS information is used as a refinement of the INS information: the GNSS information is used to counteract the intrinsic derivation of the INS solution, correcting the INS trajectory. Pseudorange prediction and data fusion through the EKF are generally software routines running on a microprocessor. Tightly-integrated systems improve the navigation performance, mainly in terms of positioning robustness, but as a counterpart, this approach adds complexity, which usually means more computing power, more complex algorithms and software.

According to the authors' experience, the expected position accuracy of a LC system composed of low cost devices, in open sky conditions, is around 2 meters most of the time. Through simulation, we evaluated the performance of the LC against the TC in case of partial GNSS signals outages (i.e. number of satellites less than four, but not all obscured). While the LC diverges (i.e.: error higher than 50 m) after 20 seconds of GNSS signals outage, the TC provides positions for more than 60 seconds, with errors approximately lower than 35 m with 2 satellites tracked, and 25 m with 3 satellites tracked. The simulation proves that when the number of satellites is less than four, the LC technique can only rely on the INS device while the TC is still able to provide an acceptable solution by exploiting the measurement coming from the few satellites in view.

As an additional example, Figure 5.2 shows the improvement of the TC versus a standalone mass market receiver in a real case. The blue marks refer to the positions estimated by the TC architecture implemented on a real time embedded system. The red marks are the positions estimated by a standalone mass market receiver. For a fair comparison of the performance, we used the same antenna for both the embedded system and the receiver.

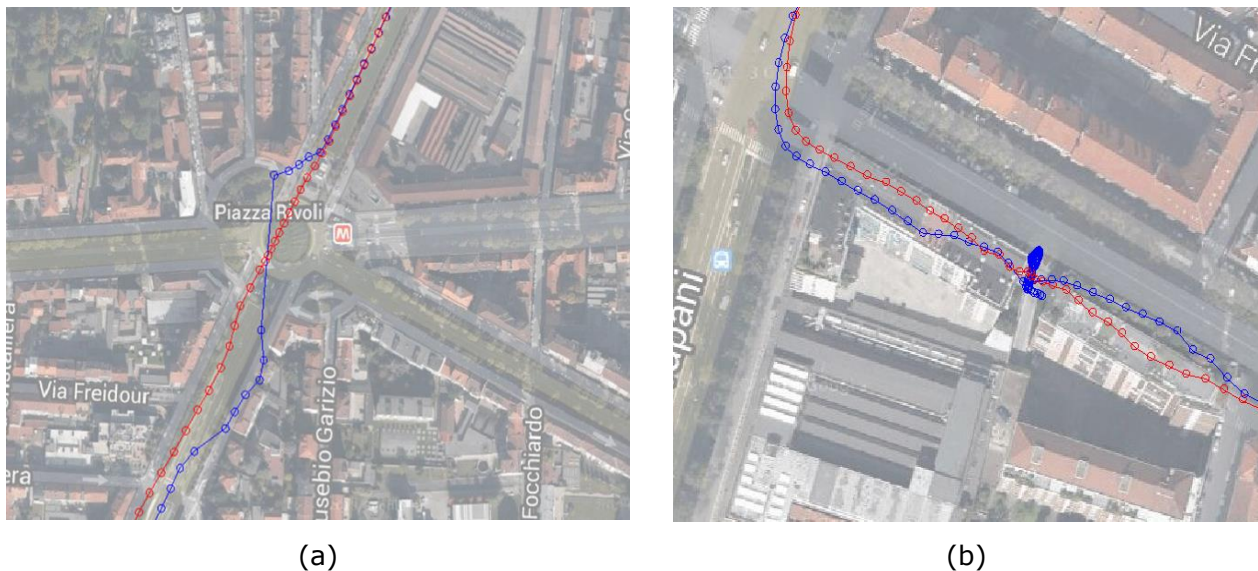


Figure 5.2: Comparison between GNSS standalone positioning (blue) and TC integration between GNSS and IMU (red). (a) passage through a city tunnel and (b) parallel street lanes with trees in the surrounding

Figure 5.2 (a) shows that the TC provides accurate positions, when the driver passed through a tunnel. Clearly, the standalone receiver cannot handle such an outage and provides positions affected by an error on the order of 20-25 meters. Even if in this case a map matching algorithm could be able to smooth the error out, there are situations in which small errors are amplified by the map matching. An example is reported in Figure 5.2 (b). Errors on the order of 10 meters (see the blue marks in the middle of the figure) can induce the map

matching to place the vehicle in a parallel street with respect to the real one. This is more likely in street surrounded by trees and buildings. On the other hand, yaw and velocity constraints on top of the TC allows for a smooth vehicle's tracks, composed by accurate positions (see the red marks).

Even if an increased positioning robustness is not perceived as a need by most of the users relying on GNSS for self-navigation, some road applications require accurate position estimates with high availability rate. This is the case of systems for the provisioning of routing guidance and alerting when the vehicle is approaching large road attributes (e.g. roundabout, bus stop). The user requirements associated to this system call for an on board unit able to estimate positions with an accuracy below 5 meters, at least 98% of the time. This level of performance are expected to be not fully ensured by mass-market standalone GNSS receivers (especially in urban environment), but a tight integration between GNSS and INS seems a viable solution to match the users requirements and handle GNSS signal outages on the order of tens of seconds.

5.3.2.2. Technological Issues of Tight Integration with IMU

In this section recalls the most challenging signal processing aspects that characterize the implementation of a GNSS/INS system. These must be considered to guarantee a proper and efficient realization of the TC algorithms:

- GPS/INS synchronization: Generally, GNSS receivers provide the internal 1PPS signal (a 1-Hz pulse) as output. Whereas this signal can be considered absolute for sensor synchronization purposes, IMUs use their own clock (nominally 100Hz), providing sensor data samples not aligned with the GNSS time reference. The design of a synchronization circuitry between the receiver and the sensors is critical and is at the basis of any algorithm fusing raw GNSS and INS measurements.
- INS calibration: The accurate calibration of the sensors is fundamental for the determination of the systematic errors. While the calibration of accelerometers can be performed off-line, the calibration of gyroscopes has to be performed in real-time under static initial conditions. Since an initial calibration could not be implemented in real system, alternative solutions (e.g.: the periodic gyro calibrations on the run) have to be considered.
- Effects of vehicle's vibrations: the IMU's raw data are not only corrupted by noise generated by the INS sensors but they are also affected by the additional noise created by the vehicle (e.g. vibration). In order to use the accelerometers and gyroscopes in a proper way a de-noising filter (e.g. low-pass filter, wavelets etc.) has to be applied. This operation adds complexity.
- Implementation of inertial mechanization equations: this issue becomes particularly important when running a TC architecture in real-time. Every IMU provides accelerometers and gyros measurements at a nominal rate at least of 100 Hz. These measurements are then used to calculate position, velocity and attitude. An efficient real-time implementation requires the split between low and high rate processing, in order to limit the computational burden of the algorithm.
- INS additional constraints: During GNSS signal outages, the vehicle's positions can be provided by the INS only. The residual noise can still affect the accuracy of INS solution, inducing a drift after a certain amount of time (e.g. it depends on the quality of INS gyroscopes and accelerometers). Therefore, in order to prevent the INS solution from such drifting additional constraints have to be included. For instance, *Non Holonomic Constraints* is a common method for vehicular applications and it is quite effective in reducing the positional error generated by the standalone IMU. Again, this strategy adds complexity although it helps to improve performance.

5.3.2.3. Perspectives toward the road sector

Leveraging on the progress in the field of sensors technology, low cost MEMS are now used in applications where the requirements in terms of package dimensions and costs are stringent. MEMS are already installed in some IVS and combined in LC with GNSS receivers (see Section 3.3.1). The data fusion of GNSS and MEMS measurements at a deeper level is a promising approach that system integrators and suppliers should carefully consider.

Criteria	Score	Justification
Performance		
Position accuracy	M/H	Recent on field tests demonstrated that the increased robustness of TC GNSS/INS systems results into an increased accuracy, especially in environments with trees and short tunnels
Position authenticity	M	GNSS receiver coupled with an IMU provides protection by effectively cross-checking the receiver's velocity estimates with the integrated IMU's acceleration measurements
Robustness to interference	M	In case of short GNSS signal outages (i.e: order of tens of seconds) due to a jamming attack, the navigation system is able to provide positions leveraging on the IMU
Availability	M	TC GNSS/INS systems increases the availability of the positions estimates, because the integrated system is able to compute the PVT even when the number of satellites is lower than 4.
Position integrity	H	TC GNSS/INS systems increase the position accuracy and mitigate the effect of NLOS signals. This, in turn, reduces the probability that the positioning error is higher than the PL.
Continuity	M/H	Given the system available at a certain instance, TC integration provides position estimates even during subsequent GNSS signal outages, thus increasing continuity
Maturity		
Technological readiness	M/H	Although some parts of the signal processing are still complex and require adequate resources, TC GNSS/INS solutions have been demonstrated in real time with prototypes embedding low cost GNSS receivers and sensors.
Time-to-market	L/M	Results available in literature are promising and most of the complexity is associated to software routines (i.e.: integration through Kalman, sensors calibration, de-noising, non-holonomic constraints, etc.). Therefore, it is expected that new products will consider TC integration in place of LC architectures.
Cost		
Estimated cost in 2015 (current)	L/M	Considering the cost of mass-market receivers and sensors, the overall cost of a TC GNSS/INS system could be estimated in the range of [500-1000] Euro.
Estimated cost in 2025	L	It is expected that the current costs of TC GNSS/INS systems will decrease, with the

		availability of more powerful boards, microprocessors and sensors at limited costs.
Challenges		
Technological challenges	L/M	TC integration adds complexity to LC approaches. Some part of the signal processing requires careful design and test (i.e.: calibration, mitigation of vibrations, implementation of inertial mechanization equations)

5.4. MITIGATION OF STRUCTURED INTERFERING SIGNALS

Currently, there is a tremendous need to design GNSS receivers robust to structured interferences (i.e. RF spoofing attacks), since they are often employed in more complex systems. The ability to authenticate the estimated positions is an important feature of future LBSs for liability-critical applications. The authentication process is based on specific processing of the received GNSS signals and involves the detection, and possibly the mitigation, of structured RF interference over bands allocated to GNSS. Such structured interference refers to the transmission of false GNSS signals intended to deceive location processing into reporting false data [RD53]. If not detected, RF spoofing deceives GNSS receivers and causes the LBS to provide a location not associated with the actual user's position, but instead provides the location dictated by the spoofing signals without any notice. The next generation of GNSS receivers will likely embed algorithms for the authentication of the positions. From a general perspective, RF spoofing can be tackled either with

- (i) new authenticated civilian GNSS signals and
- (ii) countermeasures implemented at the receiver level.

The two are complementary and will be presented in the following Sections (5.4.2 Authenticated civilian signals, 5.4.3 Spoofing countermeasures for standalone GNSS receivers), after a short introduction of the risk associated to spoofing attacks.

5.4.1. SPOOFING RISK

The RF self-spoofing is the most likely and most dangerous type of attack for many liability critical applications in road. As an example, let's consider a system for on street parking billing that charges users on the basis of the real time spent at the parking lot. Let's us assume that the system estimates the cars position with GNSS, through on-board tags that send data to a control centre. Obviously there is a direct interest of the users to spoof the GNSS receiver inside the tag, since they would have a direct economic advantage with false positions outside the parking lot sent to the service provider.

As demonstrated by some scientists in recent publications [RD54] [RD55] [RD56] [RD57], it is not difficult to induce a mass-market receiver to compute erroneous positions, for example through simple meaconing or a simplistic spoofing attack [RD58]. Although some believe that the complexity associated with a spoofing attack is too high and makes the attack unlikely, the situation is rapidly evolving. In fact, advances in computing power will make feasible attacks carried by simple software downloaded from the internet. Such software, when combined with a relatively simple front-end design, can be used to launch highly effective attacks against the civil components of the GNSS signals at the receiver level [RD59].

Obviously, the effects of spoofing attacks against GNSS receivers are mitigated using terrestrial technologies as back up. In fact, Dedicated Short Range Communication (DSRC) or video cameras can be used to validate the data coming from GNSS sensors. However these systems could be expensive and not always applicable. Under this perspective, any method that make current receivers more robust to intentional interference can contribute to reduce the spoofing risk, providing the required level of reliability and reducing the costs of enforcement systems.

Nonetheless, it is important not to forget that the GNSS signal is not the sole weak link of the "trustable position chain" of an LBS. The communication channel between the user and the service provider, in particular at the data encoding layer, may be subject to forgery as well. For example, if the LBS relies on smartphones, spoofing attacks can be carried out after the GNSS sensor without the need to generate false GNSS signals. For instance malicious software installed on rooted smartphones can mystify the (authentic) positions computed by a trusted GNSS receiver before they are transmitted to other users or to a control centre.

5.4.2. AUTHENTICATED CIVILIAN SIGNALS

A simple definition for GNSS signal authentication is given in [RD60] as the “*certification that a received signal is not counterfeit, that it originates from a GNSS satellite and not a spoofer.*”

As detailed in [RD61], the concept of signal authentication represents a cryptography-based countermeasure to possible spoofing attacks. It requires the presence of a cryptographically secure portion in the received signal (sometimes referred as a *security code* or *digital signature*) and it involves two subtypes of authentication:

- *Code origin authentication*: certification that the security code originates with the GNSS control segment (i.e., source authentication);
- *Code timing authentication*: certification that the security code arrives promptly (i.e., with the correct time of arrival) and intact (i.e., data integrity).

Unfortunately, position authenticity cannot be ensured by the current standalone receivers, which solely exploit the currently available civil GNSS signals [RD62]. In fact, baseline signals currently broadcast by satellites (e.g. GPS L1 C/A and Galileo E1 OS) do not include any cryptographic protection related to their origin (satellite or spoofer) and time of arrival.

Alternative solutions have recently been proposed aiming to overcome these limitations (e.g. see [RD63] [RD64] [RD65]). The idea is to exploit not only the civil signals, but to try to take advantage in some way of the hidden attributes of restricted-access GNSS signals. In fact these signals are intrinsically more robust against possible spoofing attacks, since it is difficult (and/or expensive) for an attacker to generate plausible counterfeit replicas of them (due to the presence of Navigation Message Encryption – NME – and/or Spreading Code Encryption – SCE). However, these alternative solutions try to take advantage of these cryptographic features in unconventional ways, for example by cross-comparing the raw received signal samples at two different locations (a reference server and a user/client). For this reason, these approaches are unsuitable to standalone receivers, since they need a data connection in order to send raw data to a remote authentication server, further increasing the implementation cost and complexity.

Other interesting proposals have been made for the design of standalone authentication solutions for civil applications based solely on open-access GNSS signals. For example, modifications of the current civil signal in space (or at least of the navigation message content, including some sort of digital signature in the navigation data stream) have been recommended both for the modernized GPS and the Galileo Open Service signals [RD66][RD67][RD68]. Thus, it is reasonable to expect that a position authentication mechanism will be provided in the near future within the GNSS signal itself, as an added value of the GNSS system [RD62].

In this context, some recent works [RD67][RD69] show that Galileo can achieve very good performance, including the possibility to authenticate the navigation messages of other GNSS constellations. In detail, a basic authentication capability is foreseen for the Galileo Open Service, based on the idea of authenticating the satellite navigation messages by means of digitally signing the navigation data (i.e. Navigation Message Authentication – NMA) and thus keeping the navigation message clear (i.e., unencrypted). This basic authentication solution, together with the more robust cryptographic authentication provided by the access-controlled signals of the Galileo Commercial Service (by means of NME and/or SCE, as explained in [RD69]), represent key differentiators of Galileo with respect to other systems.

It must be remarked that the exact definition and implementation of such authentication services is yet to be finalized and, especially for the Galileo Commercial Service, these technical aspects will depend on the EU member's agreement and the involvement of external service providers [RD69]. However, as soon as these authenticated signals will be available, they will be clearly suitable to vehicular applications, allowing future On-Board Units (OBUs) to perform a standalone assessment of the authenticity of the computed Position, Velocity, and Time (PVT) solution and decreasing the need for costly additional

sensors or other countermeasures to spoofing attacks. In addition, different service levels for the positioning authentication will be available, for example through the basic Open Service authentication: this choice will allow ensuring a sufficient robustness against potential spoofing attacks, depending also on the user needs, the application requirements, and the relevant regulations (e.g. Digital Tachograph, eCall).

5.4.2.1. Technological issues of signal authentication for road users

The readiness of the market to the application of authentication mechanisms is expected to depend not only on need of services enabled by authenticated signals, but also on the cost to the final user for the technological upgrade. Such **technological upgrade**, necessary to enable receivers with authentication capabilities, could be an issue for certain types of receiver architectures.

Focusing on the applicability of the signal authentication to road applications, it is important to point out that from a general point of view, current GNSS-based navigation systems for vehicles can rely on two different types of On-Board Units (OBUs):

1. the first is integrated in the vehicle dashboard and is power supplied by the vehicle power network. The GNSS receiver embedded in the OBU has no constraints related to power consumption, thus it constantly tracks the signal in space and decodes the navigation message that also contains the information useful for its authentication (i.e. digital signature bits).
2. the second is not integrated in the vehicle dashboard and can be seen as a black-box power supplied by batteries.

In the second case, mass market devices might implement power saving algorithms, when working without network power supply [RD70]. Such algorithms, described for example in the patent [RD71], are based on two different receiver working states:

- an *active* state, in which all the receiver's parts are activated, like in a standard receiver,
- and a *sleep* state, in which the RF module, the baseband and the DSP core are switched off.

By similarity to a square wave (see Figure 5.3), sometimes these types of algorithms are also named *duty-cycle tracking*.



Figure 5.3: Example of Duty-Cycle tracking scheme

According to [RD71], the sleep period (OFF state) length is programmed based on the receiver dynamics, mainly acceleration and speed, estimated during the latest active (ON) state.

The different tracking strategies of mass-market receivers have a non-negligible impact on the implementation of the GNSS signal authentication. In fact, if the GNSS receiver is power supplied by the vehicle, it can constantly decode the navigation message, including the information useful for its authentication. On the contrary, if the mass market receiver implements a duty-cycle tracking scheme, the active/sleep state parameters have to be set, by also taking into account the specific SIS authentication characteristic (i.e., the sleep period cannot be set in correspondence of the reception of the digital signature for Galileo Open Service authentication).

As demonstrated by this simple example, new signal formats enabling position authentication might have an **impact on the design of the algorithms and architectures of GNSS receivers**, mainly if they have to respect other constraints, such as low power consumption, high sensitivity, high number of channels, etc.

Finally, the client-server authentication approaches introduced in Section 5.4.2 are affected by several drawbacks, especially when considered for vehicular applications. First of all, they are not suitable for standalone receivers, since the connection to a remote server is mandatory. In addition, snapshots including raw signal samples should be collected at the receiver, possibly at pre-defined time slots and with a wide bandwidth, in order to correctly receive the restricted-access GNSS signals. In addition, a data connection with sufficient throughput is required in order to transfer the snapshots to the server. These aspects increase the complexity and the cost of the client/receiver with respect to a consumer-grade standalone device.

5.4.2.2. Perspectives toward the road sector

Galileo will broadcast authenticated civil signals on two frequency bands, the E1 (OS authenticated signals, expected in the near future as an added value feature with respect to baseline OS signals) and E6 (CS signals). Authentication from satellites is the first barrier against RF spoofing, therefore Galileo will contribute to make liability-critical LBS more robust to intentional attacks. Note that new authenticated signals are designed to guarantee compatibility with existing devices and signals.

As reported in very recent publications [RD69], "the re-profiling of the Galileo Safety Of Life (SOL) in the early 2010 was an important event for the Galileo CS". Therefore, even if an Interface Control Document (ICD) of the authenticated E1 and E6 signals has not been released yet, many believe that an intense effort is being carried out to have the signal transmitted in the next years.

Criteria	Score	Justification
Performance		
Position authenticity	H	The availability of authenticated civilian GNSS signals represents a cornerstone for assuring that the position is derived from true (not counterfeit) satellite signals.
Maturity		
Technological readiness	M/H	Approaches based on client-server architectures are already available in the form of prototypes or ready-to-market services (high maturity). Interesting standalone authentication solutions based solely on civil GNSS signals have recently been proposed (medium maturity, proof-of-concept level).
Time-to-market	L/M	Ready-to-market client-server services are available. On the other hand, the time to market of standalone authentication solutions depends on when the definition of the authenticated signals will be finalized.
Cost		
Estimated cost in 2015 (current)	M/H	Currently available client-server authentication approaches increase the complexity and the cost of the client/receiver with respect to a consumer-grade standalone (unauthenticated) device.
Estimated cost in 2025	L/M	A reduction of the receiver cost can be foreseen in

		the near future, as soon as civil authenticated signals will be available. Solutions based on these signals will decrease the cost for additional sensors or other anti-spoofing countermeasures.
Challenges		
Technological challenges	M	A technological upgrade is necessary to enable civil receivers with position authentication capabilities. The authentication might have an impact on the design of the algorithms and architectures of GNSS receivers, implying coexistence issues (e.g. duty-cycle tracking).
Framework conditions (i.e. regulation and standards)	M/H	The ICD definition and the implementation of Galileo authentication services are yet to be finalized in the following months.

5.4.3. SPOOFING COUNTERMEASURES FOR STANDALONE GNSS RECEIVERS

Together with the design of encrypted GNSS signals for civilian use, there is a growing interest towards standalone receiver-based defences that process the received signal and determine if it is genuine or not. Such interest is clearly driven by the fact that GPS, currently the most used GNSS, does not incorporate authentication means in its civilian signals, due both to institutional priorities and to long procurement and deployment cycles [RD72].

Generally, most of anti-spoofing techniques for standalone receivers work at the base band signal processing level and just aim at detecting possible false signals, without attempting to mitigate or remove them. A very clear and detailed analysis on spoofing countermeasures was provided by the authors of [RD73], where some techniques were roughly classified as spoofing detectors (i.e.: they discriminate the presence of spoofing signals, without necessarily mitigate the effect of the attack) and spoofing mitigation (i.e.: they attempt to neutralize the detected spoofing signals, restoring the correct positioning capabilities of the receiver).

Several types of countermeasures have been proposed with different characteristics in terms of complexity, performance and cost. Considering liability-critical applications, if the LBS does not use enforcement systems to validate GNSS-related data, there might be the risk that the LBS is not protected from self-spoofing attacks. Therefore, any countermeasure against spoofing assumes a role of primary importance.

Navigation systems integrated in the vehicle dashboard evidently offers some advantages, as the GNSS receiver can be easily coupled with external sensors and the consistency check with other solutions is actually an effective strategy to detect false positions [RD73]. With this anti-spoofing technique, the receiver compares the solution extracted by the received GNSS signals to other position and navigation solutions and the augmenting data from auxiliary devices such as inertial measurement units (IMUs) helps the receiver to discriminate the spoofing threat. In this specific case, the sensors outputs (e.g., acceleration and angular velocity in the case of IMU) are compared with the navigation solution and the consistency can be verified.

For navigation systems not integrated in the vehicles (e.g.: OBUs relying on standalone GNSS receiver, smartphones, etc.), methods for signal authentication are fundamental. Anti-spoofing techniques suitable to standalone GNSS receivers are based on [RD61] [RD57]:

- measurements consistency checks;
- methods borrowed from the Signal Quality Monitoring (SQM);
- spatial signal processing (i.e. direction of arrival comparison with an antenna array, pairwise correlation in a synthetic antenna array, multi-antenna beam forming and null steering);

- time of arrival discrimination (focusing on the PRN code and data bit latency in spoofing signals);
- distribution analysis of the correlator outputs (monitoring possible fluctuations due to the interaction between the authentic and spoofing signals);
- vestigial signal defence (based on the fact that the spoofer generally does not suppress the authentic signals)
- Receiver Autonomous Integrity Monitoring (RAIM, suitable to detect anomalies in pseudorange measurements).

The list is not exhaustive and reports only the methods most known in literature.

5.4.3.1. Technological issues of spoofing countermeasures for standalone receivers

At the time of writing, low cost receivers for road applications do not feature spoofing mitigation techniques. The complexity of the countermeasures is certainly the main key factor to consider in the design of the next generation of receivers, because they are thought for consumer grade devices with limited cost.

- Measurements consistency checks can prevent the most simple spoofing attacks (i.e.: direct spoofing attacks) and add a negligible level of complexity to the conventional processing. However, their effectiveness is limited, because they fail against the self-spoofing intermediate attack, that is considered the most likely risk in road liability applications.
- Methods based on spatial signal processing (i.e. antenna arrays) or vestigial signal defences shows very good performance in terms of protections against spoofing attacks. However, they are rather complex, require additional hardware and heavy computational burdens and are generally proposed for high-end receivers to be used in applications such as aviation.
- A good compromise between performance and complexity is represented by the methods borrowed from the SQM. However, these methods do not always discriminate false GNSS signals and multipath and might trigger false alarms, mainly in urban environments, where the presence of multipath is likely. The performances of these methods are promising, but a clear assessment of the methods in terms of a high *Probability of Detection* and low *Probability of False Alarm* needs to be proved.
- The use of back-up technologies to validate the GNSS data seems appropriated for road applications, because several sensors not based on GNSS are available on board of the vehicles. Examples are IMUs and odometers, GPRS/3G modems and in general any communication device that could be used for positioning.

From a general perspective, we believe that the signal authentication proposed for the Galileo E1 OS is a viable solution to strongly reduce the risk of spoofing attempts in liability-critical LBS. It requires few changes (at software level) of the conventional GNSS receiver architecture and reduces the need of additional anti-spoofing standalone techniques.

5.4.3.2. Perspective towards the road sector

Spoofing countermeasures at the receiver level are complementary to signal authentication and contribute to make GNSS receivers more robust against intentional interfering signals. Complex techniques, such as the antenna array are still too expensive (even if they provide excellent performance in terms of position authenticity). On the other hand, in the short term receiver manufacturers will likely consider methods based on data fusion from other sources. Examples are the integration with INS, odometers and the use of signal of opportunity as well

as the integration with cellular network. Techniques based on advanced signal processing, implemented through a new software release, are of interest for low cost, mass market receivers. Recent facts demonstrated how self-spoofing is relatively easy with low cost equipment. Thus, the integration of spoofing countermeasures in mass-market receivers will be likely in the upcoming years.

Criteria	Score	Justification
Performance		
Position authenticity	M	From a general perspective, any method for RF spoofing mitigation increases the level of reliability of the estimated PVT
Maturity		
Technological readiness	M	<p>Some of the countermeasures proposed in literature show promising performance, but they are too complex (i.e.: antenna arrays), requiring additional hardware components and cannot be used in low cost applications.</p> <p>Other techniques based on advanced signal processing have been demonstrated in receiver prototypes/SW receivers and can be considered more mature for practical applications.</p> <p>The lack of minimum performance requirements in terms of position authenticity for SCA and LCA can be considered a limit.</p>
Time-to-market	M	The time-to-market depends on the specific type of countermeasure. It is expected that as soon as the risk of RF spoofing will be perceived as real, new products will start featuring basic, but effective, countermeasures.
Cost		
Estimated cost in 2015 (current)	N.A	State of the art mass market receivers do not feature advanced spoofing countermeasures, mainly because the RF spoofing is not yet perceived as a real threat.
Estimated cost in 2025	L	<p>Already in a few years, it is expected that mass-market receivers will be able to receive authenticated GNSS signals (i.e.: the Galileo authenticated OS), complementing the ability of mitigating RF spoofing attempts with advanced signal processing, mainly through data fusion with other sensors.</p> <p>The associate cost is considered low, as most of the improvements are expected from new software routines.</p>
Challenges		
Technological challenges	M	At the moment, most effective anti-spoofing techniques are too complex and expensive.
Framework conditions (i.e. regulation and standards)	M	Missing performance bounds in terms of probability of detection / probability of false alarm to use during the assessment of standalone countermeasures.

5.5. INTEGRATION WITH SIGNALS OF OPPORTUNITY

GNSS receivers are widely used in many applications for positioning, navigation and timing, where the users are often located in urban or indoor areas. However these GNSS hostile environments provide new challenges, due to the massive buildings and obstructions, which make the view of open sky almost impossible. Therefore the GNSS only positioning will experience degraded performance in terms of availability, accuracy and reliability.

Fortunately in these areas many local networks are implemented and deployed, such as for example digital television signals, cellular networks, and Wi-Fi. They were originally designed for other purposes, but they can be used for positioning, thanks to some of their properties, such as a high Signal-to-Noise Ratio (SNR) [RD74]. For this reason, they are generally denoted as **Signals of Opportunity** (SoO) when exploited for positioning purposes [RD75].

Some recent efforts have been done to integrate SoO and GNSS or to replace GNSS signals when not available. However, it must be pointed out **that there is no single alternative that represents a true replacement for GNSS location capability, but there are many that can complement and augment satellite-based systems well**. Some examples of different technologies and approaches that can be combined with GNSS to create a system meeting requirements that are not achievable by GNSS alone are provided for example in [RD76] and references therein.

Among possible alternative solutions, location technologies based on RF signals represent more flexible approaches with respect to non-RF approaches, which in most cases feature a limited transmission range of the signals (e.g. ultrasound, vision, infrared, smart floors/furniture). For example, ultrasound-based systems can have very fine precision but are strictly limited to line of sight operation and highly subject to environmental noise [RD77]. On the other hand, RF propagation can be used for close-in applications as well as those applied over hundreds of kilometres. However, in many cases where RF has superior range it does so at the expense of precision.

Numerous types of **RF location technologies** have been implemented over the years and can be break down into five major types:

1. *Proximity-based* approaches, including contact and near-contact sensors (e.g. RFID);
2. *Direction-finding* or *angle-of-arrival*, where two or more receivers can be used to triangulate on the two-dimensional horizontal location of the transmitter;
3. *Doppler*, exploiting the frequency shift on the received signals (Doppler effect) in order to estimate the relative velocity and then distance between receiver and transmitters;
4. *Signal strength*, where the estimated signal power (or other signal-based metrics) are used to form an estimate of the range, often referenced to previously stored location information in a database (otherwise known as *RF fingerprinting*);
5. *Timing* or *phase*, using measurements of the received phase of the RF signal or an additional timing modulation on the signals to estimate the range between transmitter and receiver (as in the case for GNSS).

Further details on these different approaches are provided in [RD76], where the following technologies and their integration with GNSS are also discussed:

- RF IDentification (RFID),
- Bluetooth (IEEE 802.15),
- Wi-Fi (IEEE 802.11 b/g/n),
- ZigBee (IEEE 802.15.4),
- Terrestrial network-based systems - cellular networks (2G, 3G, 4G LTE),
- Ultra-WideBand (UWB),
- Pseudo-satellites (or pseudolites),
- Indoor GNSS repeaters (or synchrolites),
- Self-synchronizing networks (e.g. LocataLite),
- Digital television signals.

Since **digital television signals are often mentioned as one of the most promising option for the exploitation as signals of opportunity**, next section will focus on them.

After that the integration with **terrestrial network-based systems**, which also represents another **interesting solution for road applications**, will be considered in Section 5.5.2. This chapter ends with a discussion on technologies related to Dedicated Short Range Communications (DSRC), because together with GPS receivers and satellite radio, DSRC appears an essential component for automotive industry [RD79].

5.5.1. DIGITAL TELEVISION SIGNALS

5.5.1.1. Fundamentals of Digital Television Signals

Despite the underlying technical challenges, the following benefits and key advantages can be anticipated for the exploitation of Television (TV) signals for positioning purposes [RD76]:

- TV channels are **broadcast all over the world**;
- They **contain significantly more power (over 40 dB more) compared to GNSS signals** at the surface of the Earth;
- TV signals are transmitted at a **lower frequency than GNSS signals**, giving **better structure penetration** (pass-through walls);
- They occupy a **relatively high bandwidth** (e.g. 6 MHz);
- All digital and analog TV standards **contain frame synchronization codes**, thus they can be potentially used for positioning with some adjustments on TV receivers, treating TV transmitting towers as GNSS pseudo-satellites on the ground;
- This solution also offers **frequency diversity**, because TV signals are allocated on different bands with respect to GNSS.

Furthermore, their integration with GNSS receivers is expected to reinforce both systems and open a door to universal positioning services, covering anywhere and anytime [RD78].

For digital television four different protocols exist, as shown in Figure 5.4. They are **Digital Video Broadcast-Terrestrial (DVB-T)**, Advanced Television System Committee (ATSC), Integrated Services Digital Broadcasting-Terrestrial (ISDB-T), and Digital Terrestrial Multimedia Broadcasting (DTMB).

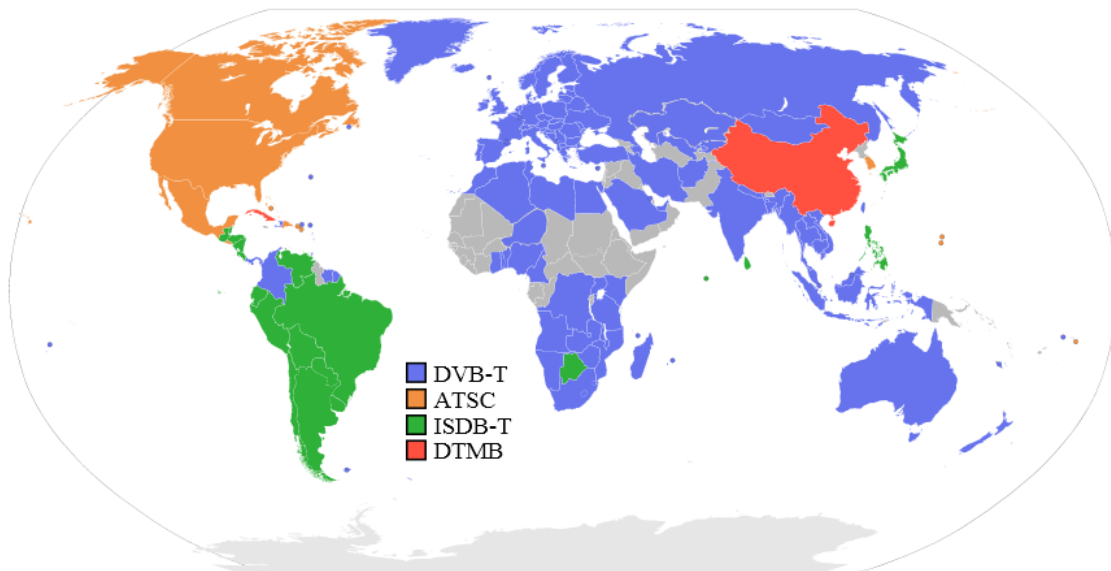


Figure 5.4: Digital terrestrial television systems worldwide (source: [RD80]).

In Europe and some other countries, the DVB-T is used as the standard for digital television, including its extension called Digital Video Broadcast-Second Generation Terrestrial (DVB-T2). DVB-T signals are located in Very High Frequency (VHF) and Ultra High Frequency (UHF) bandwidth, actually 174–230 MHz and 470–862 MHz. The 470–862 MHz frequency band is also associated to DVB-Handheld (DVB-H), which is designed for mobile users and derived from the DVB-T standard. DVB-T signals are much more used and available than DVB-H [RD75].

The DVB-T standard adopts the Orthogonal Frequency Division Multiplexing (OFDM) technique. Therefore the whole bandwidth is divided into many subcarriers, in which the **pilot subcarriers** are included. These pilot subcarriers can be used to estimate the ranges between the receiver and different emitters with a mechanism similar to the one used by GNSS receivers. Since the SNR requirement for ranging is much lower than the one required by the television service, the receiver is able to see several emitters in one point. If three or more signals are successfully processed, the receiver can provide a DVB-T only the positioning; otherwise, it can be used to assist GNSS [RD74].

Two different network types can be deployed for broadcasting DVB-T signals [RD81]:

- *Multi-Frequency Network* (MFN) and
- *Single Frequency Network* (SFN).

In MFN, different emitters transmit the same signal on different frequencies, and they are not exactly synchronized; while in SFN, all the emitters simultaneously transmit the same signal in the same frequency. The **synchronization is typically provided by some professional GPS timing receivers**, and this represents a key point when DVB-T signals are used for positioning purposes.

5.5.1.2. Technological Issues of Digital Television Signals

The following issues related to the use of DVB-T signals for positioning must be pointed out:

- The transmission of the **DVB-T emitter identifier (ID)** is optional;
- **Accurate knowledge of locations of DVB-T emitters is needed** (e.g. from map/database);
- Achievable **accuracy performance is limited** in highly challenging urban scenarios.

Focusing on the first point (optional transmission of the emitter ID), it must be noticed that this is not an issue for the provision of the DVB-T service, but it is a problem to be solved when the signals are used for positioning. **Some companies (for example, RAI in Italy) already transmit the emitter ID** within their bit streams, which are then completely equal apart from this small difference. This causes a (very limited) penalty, but is very useful for network management and control. It is clear that this extra-information can be very useful also for positioning purposes, since it highly simplifies the association of each received DVB-T signal to the corresponding emitter [RD74].

Some actions could be adopted in the future in order to convince all the network operators to transmit the emitter ID. These actions would foster the adoption of DVB-T signals for positioning applications. In fact, the availability of the emitter ID and the knowledge of the locations of the DVB-T transmitters (e.g. from a map or a database) would increase the potential of hybrid GNSS/DVB-T approaches for a seamless positioning service in urban/indoor areas, even making feasible standalone solutions based on DVB-T signals only.

Even though the emitter ID is not available, other alternative approaches have already been proposed and investigated. A possible positioning method suitable to DVB-T Single Frequency Networks has been presented in [RD74]. In this case, a **hybrid GNSS/DVB-T receiver** is assumed, where GNSS signals are used in a first initialization phase to solve the ambiguities referring to the various DVB-T emitters (not broadcasting their IDs). When this phase is completed, the user position can be obtained by using DVB-T signals when the user enters a GNSS-blocked area. The method has been tested by simulation in a dynamic scenario, demonstrating that a mean position error as good as 6 m can be achieved if the user can correctly associate the signals to the DVB-T emitters.

Another alternative architecture for exploiting TV broadcasts can be based on a **client-server approach** [RD76]. A reference receiver in a local monitor station can measure the signal timing of the television signals and GNSS signals, reporting this information to a location server. The mobile receiver to be located measures the Time Of Arrival (TOA) of the television and GNSS signals and forwards this to the location server to compute a range-based solution. In a system implementation, **combined TV+GPS location accuracies in a highly challenging urban environment have been reported in below 50 m CEP [RD78]**. Due to such achievable accuracy performance, even if limited in challenging scenarios, it would represent an appealing approach for applications focusing on high availability, requiring **seamless outdoor-indoor positioning capability, but with relaxed accuracy requirements** (e.g. logistics).

5.5.1.3. Perspectives toward the road sector

The results presented in previous sections (e.g. see [RD75] and references therein) allows us to conclude that hybrid solutions based on GNSS and digital TV signals (especially DVB-T in Europe) represent an interesting technological solution in **the medium term**. One key element is the **increasing diffusion of on-board infotainment systems, that already include digital radio and DVB-T receivers**. These are at the basis for the processing of DVB-T signals to improve the performance of standalone GNSS receivers. In addition, DVB-T can be a backup technology anytime GNSS signals are not available (i.e.: due to a jamming attack), at least to provide rough estimates of the user's position.

However, the current lack of standards is a barrier. Standardization and regulation actions would possibly reduce the time-to-market, that at the time of writing cannot be considered lower than 10 years.

Criteria	Score	Justification
Performance		
Position authenticity	M	Simple but effective spoofing detectors can be based on the consistency checks between positions computed using GNSS signals and those obtained with DVB-T.
Robustness to interference	L/M	In case of GNSS signal outages due to a jamming attack, the navigation system can rely on DVB-T only to estimate the user's position.
Availability	M	Hybrid DVB-T/GNSS approaches increase the position availability w.r.t. GNSS only. DVB-T seen as a backup technology when GNSS signals are not available. Moderate accuracy performance in highly challenging urban scenarios (50 m CEP).
Maturity		
Technological readiness	M	Proof-of-concept algorithms and solutions already demonstrated.
Time-to-market	M	Possible regulation/standardization actions would possibly reduce the time-to-market.
Cost		
Estimated cost in 2015 (current)	M/H	Due to the need of accurate localization of DVB-T emitters and high costs for system engineering/deployment.
Estimated cost in 2025	L/M	Possible regulation/standardization actions would foster the market adoption, leading to a marginal cost for the equipment.
Challenges		
Technological challenges	L/M	Accurate knowledge of locations of DVB-T emitters is needed (e.g. map/database obtained from a survey).
Framework conditions (i.e. regulation and standards)	M	Hybrid DVB-T/GNSS approaches not yet standardized or regulated.

5.5.2. TERRESTRIAL NETWORK-BASED SYSTEMS

5.5.2.1. Fundamentals of Terrestrial Network-Based Systems

The term **terrestrial network-based positioning and navigation systems** refers to those location systems that use wireless technologies entirely deployed on the ground. The most used wireless technologies of this kind are [RD13]:

- Cellular networks,
- Wireless systems based on Ultra-WideBand (UWB),
- Wireless Local Area Network (WLAN),
- Wireless Sensor Network (WSN) technologies.

Terrestrial network-based positioning systems can also be referred to as *local* or *short-range systems*, because their coverage area is restricted to the region where they are deployed. Thus, they differ from GNSS, whose coverage is *global*.

In addition, most of these terrestrial systems were designed and optimized having in mind communication and data transmission services, but not positioning. Their use for positioning purposes is motivated by the trend toward personal use of navigation systems associated

with LBSs, requiring positioning devices able to seamlessly work under various, variable, and critical conditions, such as inside warehouses, multi-storeyed buildings, underground stores and parking, and indoor commercial and office campuses. Unfortunately, GNSS indoor reception is dramatically impaired by strong attenuation due to walls and slabs and by the multipath effect. Therefore, urban and indoor environments open challenging issues for GNSS signal processing and receiver design, to which the integration with terrestrial network-based systems try to give solution.

When there is an indoor receiver, GNSS signal reception is characterized by a strongly attenuated direct component and several reflected or scattered multipath components. The attenuation affecting the direct path can range from 10 to 25 dB, depending on the nature of the concrete, thus reducing the carrier power the receiver has to deal with from about -160 dBW to even -190 dBW; however, the nominal sensitivity in signal acquisition of current commercial receivers is around -178 dBW. Furthermore, indoor multipath and scattering effects become far more harmful. In such conditions, the use of basic GNSS receivers is really questionable and substantially different approaches have to be adopted.

Nowadays much research is focused on the use of terrestrial wireless technology as a means of developing positioning and navigation systems that work where satellite systems fail. New LBSs require a certain level of location accuracy to be met by the positioning systems, in spite of all the propagation problems typical of wireless communication, such as channel fading, low SNR, multiuser interference, and multipath conditions.

Pioneering work on indoor positioning dates back to more than 10 years ago, but a lot of work is still going on to refine and get past those pioneering ideas, both in academia and industry. Several wireless technologies have been studied for indoor positioning and their distinguishing elements are:

- The positioning algorithm, which may use various types of measurement of the signal, such as Time Of Arrival (TOA), Angle of arrival (AOA), and Received Signal Strength (RSS).
- The physical layer of the network infrastructure used to communicate with the user's terminal.

Among possible terrestrial network-based systems, recently there has been a large interest in exploiting **cellular networks** to provide positioning services. Thus, next sections will focus on the advantages and open issues related to the use of this specific technology in road applications.

5.5.2.2. Positioning in cellular networks

Nowadays cellular networks are widely deployed in all developed countries, relying on a set of base stations. Each Base Station (BS) covers a cell, with a coverage radius up to about tens of kilometres.

Such cellular networks can be used for positioning purposes, without the necessity to deploy ad hoc and expensive wireless infrastructures. Unfortunately, 2G and 3G cellular standards were designed and optimized having in mind data and voice communication services but not positioning.

The simplest method to obtain some coarse location information is by using the *Cell Identification* (Cell ID) as proximity indicator. The localization accuracy will be of the order of the cell size, enough for some applications if small and densely distributed cells (*picocells*) are deployed. For larger cells, some more elaborate techniques have to be used.

Potentially, 2G/3G cellular physical layer can provide ranging information through *Time Of Arrival* (TOA) estimation, even though the relatively small bandwidth limits the achievable time resolution (e.g., 1 μ s for GSM, about 200 ns for 3G systems).

The most widespread positioning technology in cellular networks is based on *Time Difference Of Arrival* (TDOA). For instance, GSM location is based on the existing *Observed Time Difference* (OTD). OTD evaluates the time difference between signals traveling from two

different BSs to an MS. At least three visible BSs are needed to estimate the MS position, obtained by intersecting hyperbolic lines having foci at the BSs' positions. The final location estimation accuracies in GSM-based location systems using OTD ranges from 50 to 500 m.

The signal parameter estimation used in UMTS networks is the *Observed TDOA* (OTDOA), which is based on the TDOA approach. Anyway, the **accuracy of cellular-based positioning is quite modest**, for this reason recent location estimation algorithms try to exploit any available information about the environment (e.g., fading conditions, Doppler frequency, and network topology) to **attain higher accuracy through data fusion methods** [RD13].

5.5.2.3. Technological Issues of Positioning in Cellular Networks

The approaches for positioning in cellular networks (2G, 3G, or 4G) can be considered as a **mature technology**. In fact, such approaches are **already standardized and adopted in commercial devices** for providing location services, also providing AGNSS data to the user receivers.

However, the following issues must be remarked:

- The potential **location estimation accuracy** achievable exploiting cellular network signals is **limited in challenging scenarios** (e.g. 50 to 500 m);
- These signals are impaired by **typical propagation problems of wireless communication** (channel fading, low SNR, multiuser interference, and multipath);
- The positioning performances are also related to the **geometry of the cells and the density of the BSs** in proximity of the user receiver.

5.5.2.4. Perspectives toward the road sector

As stated in [RD33], in the coming years In-Vehicle Systems (IVS) – enabled to communicate through cellular networks – will progressively replace PNDs. Integrated navigation/communication systems are **already adopted in many road applications** (e.g. fleet tracking), then it is expected that more and more applications and services will take advantage of **integrated navigation/communication services** in the short term (e.g. eCall).

Moreover, the widespread use of consumer devices (i.e.: smartphones and tablets) embedding a GNSS chipset motivate the integration of the two technologies, that will be at the basis of new services at limited costs. The standardization already addressed some aspects of LBS based on GNSS and cellular networks¹⁴.

Signals from cellular networks can be also used to implement trilateration methods. In this case, cellular networks can be a backup technology anytime GNSS signals are not available (i.e.: due to a jamming attack), at least to provide rough estimates of the user's position.

¹⁴ See for example <http://www.etsi.org/about/what-we-do/global-collaboration/3gpp>

Criteria	Score	Justification
Performance		
TTFF	M/H	Increased TTFF thanks to AGNSS methods.
Position authenticity	M	Simple but effective spoofing detectors can be based on the consistency checks between positions computed using GNSS signals and those obtained with cellular network. Also, a simple technique able to match the requirements of some applications consists in comparing the GNSS position with the area covered by a specific network cell ID.
Robustness to interference	M	In case of GNSS signal outages due to a jamming attack, the navigation system can rely on cellular networks only as a backup to estimate the user's position.
GNSS sensitivity	M	Aiding from the cellular network can include the navigation message data bits. This allows for a longer integration time, that is a way to enhance GNSS sensitivity.
Availability	M	Increased availability of (at least coarse) positioning information w.r.t. GNSS only. Limited location estimation accuracy in challenging scenarios (e.g. 50 to 500 m). Performance dependent on the positioning method (Cell ID, OTD, OTDOA) and on the geometry/density of the cells.
Maturity		
Technological readiness	M/H	Mature technology for integrated navigation/communication (e.g. eCall). Good perspectives for cooperative localization approaches (e.g. peer-to-peer).
Time-to-market	L	Already adopted in some road applications.
Cost		
Estimated cost in 2015 (current)	L/M	Moderate increase of the cost/complexity of the vehicle on-board equipment. Accurate localization of BSs needed.
Estimated cost in 2025	L	Marginal cost in future vehicles (always connected to wireless networks).
Challenges		
Technological challenges	M	Cellular signals impaired by typical wireless propagation problems (channel fading, low SNR, multiuser interference, and multipath). Improvements on the achievable positioning performance expected/required in next generation cellular networks.
Framework conditions (i.e. regulation and standards)	L/M	Already standardized approaches and signals. Pressing needs for road applications, requiring better positioning performance.

5.5.3. DEDICATED SHORT RANGE COMMUNICATION (DSRC) TECHNOLOGY

5.5.3.1. Fundamentals of DSRC

DSRC provide communications between vehicles and the roadside in specific locations. DSRC are used at the roadside for vehicle applications such as tolling, smart parking systems, and between vehicles [RD77]. This last is for more advanced concepts, still under investigation, to support adaptive cruise control.

DSRC are for data-only systems and operate on frequencies allocated in the microwave region (i.e.: between 5,725 MHz to 5,875 MHz) and as such they use conveniently small antennas, suitable for easy integration into small tags. The technology is part of what can be considered to be RFID, since a principal function of the tag is usually to identify itself for validation. Roughly speaking, DSRC systems consist of the Road Side Units (RSUs) and the On Board Units (OBUs) with transceivers and transponders. The DSRC standards specify the operational frequencies and system bandwidths, but also allow for optional frequencies which are covered (within Europe) by national regulations.

DSRC systems are used in the majority of European Union countries, but these systems are currently not totally compatible. Therefore, standardization is essential in order to ensure pan-European interoperability, particularly for applications such as electronic fee collection, for which the European imposes a need for interoperability of systems. EGNSS, being a space technology with global coverage, helps to overcome the system incompatibility. Commercial OBUs with DSRC integrated with GNSS are already available on the market, see for example [RD82]. For road tolling **the use of GNSS enables migration from, and interoperability with, existing DSRC based charging systems.**

In this context, the standardization of architectures and protocols is very important, because it ensures compatibility and interoperability within a multi-vendor environment. The base standards for DSRC have been developed by CEN [RD83]. The ETSI work on DSRC complements the CEN activity in response to the European Commission Mandate (M/338 - issued to ETSI, CEN and CENELEC) in support of interoperability of electronic road toll systems.

- CEN has developed the DSRC base standards, upon which the ETSI work is based;
- Technical Committee TC 204 of the International Organization for Standardization (ISO) is working on Intelligent Transport Systems, and its TC22 is working on in-car equipment;
- The ICT Standards Board has an Intelligent Transport Systems Steering Group.

5.5.3.2. DSRC as signal of opportunity to improve GNSS performance

From a general perspective, the availability of OBUs integrating GNSS and DSRC makes possible the processing of DSRC signals to improve the performance of the GNSS receiver. This started to be investigated in the recent years, because vehicular applications are among the most demanding systems for accurate position information. Although most of vehicular navigation systems can generally rely on satellite based positioning, other emerging systems in the road domain may not use GNSS data only, due to their limited accuracy and availability. Safety-related applications, such as collision avoidance or lane level guidance, are some examples. Over the past decade, some innovative approaches have been presented to enhance position accuracy within vehicular networks. Most of these are based on communicating data among the nodes of a network: this concept is often referred to as Cooperative Positioning (CP) [RD84].

A variety of modern CP techniques based on vehicular communication and RFID have been proposed. Some of the most promising are based on algorithms that use the Doppler shift between a the target node and its neighbours to estimate ranges [RD85]. The main motive behind this choice is that the Doppler shift is considerably less distorted by channel fading and multipath, which are dominant sources of errors that impact other techniques, like

Received Signal Strength (RSS), Time Of Arrival (TOA) and Time Difference of Arrival (TDOA). Another advantage of the method presented in [RD85] and [RD86] is that it does not require synchronization between participating nodes. Although at the time of writing a small percentage of vehicles is equipped with OBU integrating GNSS and DSRC, some experts believe that vehicular communication platforms will be standard in the near future [RD87]. The use of DSRC signals to help GNSS in challenging environments allows for an improvement on the horizontal accuracy. The results reported in [RD85] indicate a reduced horizontal positioning error of about 50% respect to standalone GNSS receivers. However, even if the integration of GNSS and DSRC is a technology to look at in the next years, several open points remains before a real deployment of cooperative positioning with DSRC.

5.5.3.3. Technological Issues of combination of GNSS with DSRC

The use of GNSS combined with DSRC for road tolling can be considered a mature technology and commercial OBUs are now available on the market, with a cost in the range of [120-200] Euros per unit. These OBUs are thought to preserve the interoperability of different national tolling systems and ease the migration from DSRC-based to GNSS-based charging schemes.

On the other hand, the processing of DSRC signals as signals of opportunity is a promising technology, but with a lower TRL and with open issues to be solved. The most important are summarized below.

- The distance between the nodes (i.e.: vehicles equipped with DSRC tags) is assumed to be estimated by some radio-ranging methods (e.g.: TOA, TDOA), but the constraints and the limits imposed by the communication medium and by the mobile environment corrupt the measurement accuracy and are not yet well acknowledged.
- A more robust alternative to measure the distance between nodes is based on the estimate of the Doppler shift between the nominal carrier frequency and the frequency of the received signals. However, this method has not been assessed through an intense on-field measurement campaign. Results are promising, but they have been obtained in simulation, with doubtful assumptions of some parameters (i.e.: traffic intensity, number of peers surrounding the targets, etc.) that could impact the final performance. Results mainly refer to a highway scenario, whereas more challenging environments should be considered.
- CP relies on measurements from other vehicles, that must be equipped with OBUs, integrating GNSS and DRSC. The higher number of vehicles, the better. Although some experts believe that DSRC will be a standard in the next generation of vehicles, at the time of writing the use of those OBUs is limited.

5.5.3.4. Perspectives toward the road sector

All the vehicles already equipped with an OBU integrating GNSS and DSRC - for the purposes of road tolling – might exploit DSRC technology in supporting positioning authenticity (at least at discrete locations within the coverage area of RSUs), being this a significant need for PCAs. Moreover, assuming that [RD79]'s estimates will be confirmed, the effectiveness of DSRC in supporting a more accurate positioning appears to be strongly limited by the poor quality of the ranging measurements.

Criteria	Score	Justification
Performance		
Availability	M	Assuming a sufficient numbers of vehicles equipped with integrated GNSS+DSRC, increased availability of the vehicle positions, mainly in areas with poor visibility of the GNSS satellites.
Accuracy	M	Assuming a sufficient number of vehicles, integrated GNSS+DSRC enables Cooperative Positioning techniques that can improve the positioning performance of standalone GNSS receivers. Early investigations demonstrated an improvement up to 50% in some road scenarios. Performances depend by a number of parameters (i.e.: number of peers, traffic intensity, external environment, etc.)
Position authenticity	M	At least at location where DSRC is available (e.g. within the coverage area of RSUs), it can be used to validate the data coming from GNSS sensors.
Maturity		
Technological readiness	H (L)	H for GNSS+DSRC used for road tolling. L for DSRC as a source of signals of opportunity.
Time-to-market	L (M/H)	L for GNSS+DSRC used for road tolling. Products already on the market. M/H for DSRC as a source of signals of opportunity.
Cost		
Estimated cost in 2015 (current)	L/M	OBUS cost in the range of [120-200] Euros per unit
Estimated cost in 2025	L	According to some estimates [RD79], DSRC will be one of the most popular technologies in the automotive sector in 2022. It is likely to assume a further reduction of the current costs.
Challenges		
Technological challenges	M/H	The major constraint related to the use of DSRC terminals as positioning modules seems related to the limits imposed by the communication medium. These do not allow for accurate ranging measurements. The poor availability of vehicles equipped with DSRC-based positioning modules limit CP techniques.
Framework conditions (i.e. regulation and standards)	L	Base standards for DSRC terminals have already been developed, at least for their conventional use as RF tags

5.6. METHODS FOR PRECISE POSITIONING

Today the design limit for the accuracy of the GPS system for a “stand-alone” receiver can be set to three to four meters, which is considered not entirely satisfactory by many users [RD88].

GNSS accuracy is plagued by various types of errors linked to either the satellite system or the physics of the electromagnetic propagation (e.g., refraction and attenuation through troposphere and ionosphere). The sum of these errors can be easily measured at any point on Earth, if the actual coordinates of a receiver are known accurately, and are likely to remain valid in the vicinity of a given point over a small period of time [RD88].

Corrections provided by reference stations (*differential augmentation*) have greatly improved the accuracy of positioning since the advent of GPS. Differential augmentation services encompass various terrestrial networks of stations deployed on a national scale and continent-wide systems developed by civil aviation authorities, which broadcast corrections via geostationary satellites (i.e., WAAS, EGNOS, MSAS).

Networks of differential stations can help receivers to achieve accuracy levels from a meter down to decimetre. But such accuracy levels are still considered insufficient for a number of civilian applications, such as surveying, some Earth observation data, precise machine guidance for off-shore exploration, mining vehicles, and automated farming [RD88]. Indeed, historically precise positioning was associated with surveying and geodesy. It is nowadays incorporated into production processes in mining, agriculture and construction. The main application has been in machine guidance and machine automation which require high levels of precision.

In order to achieve sub-decimetre level accuracy, receivers have to process carrier phase measurement as well, to obtain information about their distance from the satellites (*carrier-phase ranging*). In order to extract the correct range information from the carrier phase, which is intrinsically ambiguous, two primary approaches have been employed over the last 15 years: Real-Time Kinematic (RTK) and Precise Point Positioning (PPP). RTK and PPP are now state of the art for multiple frequency high end receivers used in agriculture, geodesy and other professional application requiring cm level accuracy. Multiple frequency high end receivers feature wide front end bandwidths and high sampling frequency, stable local oscillators and algorithms for measurements selection.

The application of methods for precise positioning with low cost, mass-market receivers is currently a research challenge.

In the following subsections we briefly review the main aspects of the two approaches and highlight the technological challenges to be faced for their introduction in the market of the ITS-enabling technologies.

5.6.1. PRECISE POINT POSITIONING (PPP)

The technical principle of Precise Point Positioning (PPP) is that measurement errors are mitigated or removed from the position calculation using sophisticated modelling techniques and correction products such as precise satellite orbit and clock corrections. GNSS corrections are generated using data from a global reference network and they can be applied anywhere on the Earth. By eliminating the need for a local reference stations, users can achieve centimetre- or decimetre-level positioning in areas where it is not practical to use traditional RTK techniques [RD89].

With respect to RTK, the major benefits offered by PPP can be summarized in [RD90]:

- absence of direct and open-sky link with a local and nearby reference station;
- global positioning approach, because its solutions are referred to a global reference frame instead of a relative positioning to the local station;

- reduction of labour and equipment cost, as well as operational logistics, since it eliminates the dependency on local base station(s).

On the other hand, significant challenges remain ascribed to PPP:

- it typically requires very long convergence times, due to the absence of a baseline that helps in fixing the carrier ambiguities;
- for very high precision (i.e.: <5 cm), the latency of the corrections matters, sometime preventing the real-time;
- in general, a more complicated processing at the receiver's side is necessary with respect to a solution which employs baselines (i.e., RTK)

5.6.1.1. PPP components

The major components of a PPP service can be identified in:

1. Correction products generated by the correction provider;
2. Delivery of the corrections to the user;
3. Computation of the position solution on-board a PPP-enabled GNSS receiver at the user end.

The *correction products* are, at least, precise GNSS satellite orbits and clocks; they may be also complemented with precise troposphere corrections [RD89] and ionosphere models [RD91]. Correction products are today available from a number of public organization (e.g., the International GNSS Service, IGS, <http://igs.cb.jpl.nasa.gov/>, the Natural Resources Canada, NRCAN, http://www.geod.nrcan.gc.ca/products-produits/ppp_dir_e.php, and Jet Propulsion Laboratory, JPL, <http://apps.gdgps.net/>, which all provide a free-of-charge service) and commercial providers (e.g., Fugro/Trimble, Veripos, NavCom, NovAtel), whose services are on a subscription basis. The corrections are generated from large, most private, receiver networks. A network consists of several tens, up to more than one hundred, of GPS reference stations located around the globe, sometimes including also GLONASS receivers. Major receiver networks are operated by IGS, JPL, StarFire (NavCom, John Deer), OmniStar (Trimble) and TerraStar (Veripos).

The *delivery of the corrections to the user* may be realized through the Internet (as in the case of IGS, which employs the Networked Transport of RTCM via Internet Protocol (NTRIP) [RD92]) or via dedicated radio channels. The preferred solution for real-time processing is broadcasting over the L-band satellite. This eliminates the need for a separate data link. Indeed, by delivering corrections over satellite, user's receivers do not need local base-station infrastructure, cellular modem or Wi-Fi radio, greatly simplifying the user's hardware configuration. The Galileo Commercial Service (CS) introduces a new approach and foresees the broadcasting of PPP data in the navigation message of the E6 signal [RD69]. On the other hand, if the real-time is not a requirement, there are several ways to obtain coordinates in PPP mode, using various scientific processing packet software (e.g., Bernese, Gipsy, WaPPP, P3) or web-based online processing services (e.g., CSRS-PPP, GAPS, APPS, magicGNSS) [RD93].

Commercial services promise near-real-time orbits and clock corrections, provided on a subscription fee basis (on the order of 1000 Euros per half a year, per receiver). Free-of-charge products are released with various latencies, which depend on the accuracy of the computed correction. For example, the accuracy and latency of the IGS products is reported in Table 5.1, extracted from <http://igs.cb.jpl.nasa.gov/components/prods.html> (accessed on Feb. 2015).

IGS Product Table [GPS Broadcast values included for comparison] -- updated for 2009!					
		Accuracy	Latency	Updates	Sample Interval
GPS Satellite Ephemerides/Satellite & Station Clocks					
Broadcast	orbits	~100 cm	real time	--	daily
	Sat. clocks	~5 ns RMS ~2.5 ns SDev			
Ultra-Rapid (predicted half)	orbits	~5 cm	real time	at 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~3 ns RMS ~1.5 ns SDev			
Ultra-Rapid (observed half)	orbits	~3 cm	3 - 9 hours	at 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~150 ps RMS ~50 ps SDev			
Rapid	orbits	~2.5 cm	17 - 41 hours	at 17 UTC daily	15 min
	Sat. & Stn. clocks	~75 ps RMS ~25 ps SDev			5 min
Final	orbits	~2.5 cm	12 - 18 days	every Thursday	15 min
	Sat. & Stn. clocks	~75 ps RMS ~20 ps SDev			Sat.: 30s Stn.: 5 min
GLONASS Satellite Ephemerides					
Final		~3 cm	12 - 18 days	every Thursday	15 min
Atmospheric Parameters					
Final tropospheric zenith path delay		4 mm	< 4 weeks	weekly	2 hours
Ultra-Rapid tropospheric zenith path delay		6 mm	2-3 hours	every 3 hours	1 hour
Final ionospheric TEC grid		2-8 TECU	~11 days	weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)
Rapid ionospheric TEC grid		2-9 TECU	<24 hours	daily	2 hours; 5 deg (lon) x 2.5 deg (lat)

Table 5.1: IGS product table.

The GDGPS System of JPL provides a global real-time map of ionospheric electron content, currently updated every 5 minutes.

The *computation of the position solution* at the receiver side entails several requirements posed on the user's receiver. First, the receiver must be enabled to retrieve all the necessary corrections, either through the Internet or via its radio channel. Second, it must carry a set of advanced algorithm to provide highly stable measurements and to adequately process the corrections to achieve positioning accuracies on the order of a few decimetres or centimetres. The final achievable positioning accuracy depends in part on the quality of the corrections and, mostly, on the quality of the user's equipment [RD90]. Of course, highly degraded environments (e.g., multipath, interference and non-line-of-sight propagation) dramatically worsen the achievable accuracy.

5.6.1.2. Error Mitigation in a PPP-enabled receiver

Advancements in GNSS positioning have, to a large degree, been due to progresses made in the modelling and mitigation of the various error sources that corrupt the measured ranges.

Error mitigation approaches in a high-precision receiver can essentially be divided into three categories:

1. Signal combinations
2. Error models
3. Externally-provided information

On top of this, the receiver must resort to carrier-phase ranging in order to exploit the cm-to-mm precision of the phase observables [RD94].

PPP can be considered at the apex of GNSS error mitigation and uses all of the approaches listed above.

For instance, to remove the effects of the ionosphere, PPP-enabled receivers typically use combinations of signals on different frequencies [RD89], [RD69], [RD90].

Troposphere errors are reduced by advanced troposphere delay models, and then further mitigated by zenith delay dynamic models [RD89].

PPP data providers supply corrections that remove the effects of satellite clock and orbit errors. There is some latency between the calculation of the satellite positions and clocks on the provider side and their use on the client side. For this reason this latency must be accommodated by the PPP filter [RD89].

PPP also requires a number of unconventional corrections to mitigate systematic effects that could cause centimetre variations in the code and phase observations [RD90]. Phase wind-up correction, satellite antenna offset, and site-displacement effects due to solid Earth tide and ocean loading are some examples [RD95]. These corrections are not considered for standard point positioning, where the accuracy remains above the meter level, nor in double-difference RTK positioning, where these effects cancel out thanks to the relative positioning.

The net effect of the PPP error mitigation is to reduce the GNSS carrier-phase measurement precision to the amount of the remaining unmitigated errors. With a high-quality PPP correction feed, this error can be reduced to only a few centimetres. However, the well-known problem of the *ambiguity* in the carrier-phase measurements still remains [RD89]. In the absence of any baseline (i.e., any known reference station nearby the user's receiver, as in the case of RTK), ambiguity fixing becomes very challenging, because the search space for the correct integer fixing is huge, and therefore it takes time to resolve [RD91][RD96][RD97]. This time is the so-called *convergence period*.

One way for improving convergence is to improve the geometry of the solution by adding additional satellites. This is the reason why *multi-constellation receivers* are preferred also for high-precision processing [RD89], [RD98].

Reference [RD89] reports convergence times on the order of 30 minutes for an horizontal accuracy of 0.2 meters (95%), using a top-grade dual-frequency receiver with real-time corrections. Similarly, [RD91] reports for the same accuracy a convergence time less than 20 minutes using a dual-frequency with non-real-time corrections ("Final" IGS orbits and clock corrections, with up to 18 days delay).

Reference [RD91] demonstrate how single-frequency PPP can achieve much faster convergence time thanks to the use of ionospheric corrections read from an external source (e.g., the Global Ionosphere Map from IGS) to correct for ionospheric delays. This way, the inter-frequency differences to remove the ionospheric effects are not needed anymore, which are known to be very noisy and amplify multipath and receiver measurements. Since the noise is not amplified in the undifferenced single-frequency measurements, convergence time is much faster [RD91]. Of course, the price is an accuracy which cannot be reduced below some decimetre.

5.6.2. REAL TIME KINEMATIC (RTK)

Real Time Kinematic (RTK) is the state of the art of some professional applications based on high end GNSS receivers employed in open sky conditions (e.g.: precision agriculture for the

control of seeding and fertilizers spreading, geodesy and surveying). These applications require centimetre level accuracy for moderated (or static) users' dynamics.

As done for the PPP, this section recalls the fundamentals of the RTK and presents some results of early investigations on the use of RTK for mass-market applications. Indeed, RTK algorithms combined with single frequency, low cost receivers represent a research topic, that arise interest in the road applications domain.

5.6.2.1. RTK fundamentals

Errors due to the signal propagation in the atmosphere, not precise satellite orbits and satellite clocks offsets are correlated in space and time. A differential system takes advantage from the fact that two receivers with a certain degree of proximity are affected by common errors, namely the errors with a strong spatial correlation, that can be mitigated. By simply differencing measurements from two synchronized receivers, spatially correlated errors are eliminated or reduced, provided that the baseline (i.e.: the geometric distance between the two receivers) is within a few kilometres. From the point of view of the implementation, two approaches are possible:

1. the error experienced by the base (i.e.: a static receiver in a known position) is estimated and sent to the rover (i.e.: the user's receiver) as a correction;
2. the measurements of both receivers are combined together (i.e.: through single or double differences), achieving the so called relative positioning between the two.

The second is the case adopted by the RTK positioning, which typically relies on double differences between pseudoranges estimated through carrier-based measurements. The result of such differences is used to estimate the baseline, that in turn is summed to the position of the base (which is known and geo-referenced) to get the user's position.

Models for carrier-based pseudorange measurements can be found in many books on GNSS (e.g.: [RD97][RD99]). Compared to code phase measurements, carrier phase is more precise but ambiguous. In fact, carrier phase measurements (in cycles) can be expressed similarly to the code phase measurements with the addition of the ambiguity term. The necessary hypothesis is that the receiver's Phase Lock Loops (PLLs) stay locked to the incoming signal carrier phase and keeps estimating its variations over time without interruptions. Thus, the main task for RTK methods is the resolution of such ambiguity, which has three fundamental characteristics:

- it is an additional unknown for the position determination;
- it is different for each satellite;
- it is a constant, supposing that a continuous lock of the carrier phase tracking loop is maintained, which is likely in open sky condition for a medium-high satellite elevation, rather difficult in other types of environments.

Once the carrier is locked by the receiver, it is able to keep trace of the change of the distance in term of phase, counting the fractional number of cycles and accumulating them over time (the so-called *accumulated Doppler*). These measured phases are added to the unknown ambiguity (that is an integer if the double difference approach is used) and become valid for ranging (i.e. satellite-user distance) and for the computation of the baseline. The computation of this ambiguity requires significant computational effort, because the algorithms seek a set of suitable values in a finite search space.

Then, once the integer ambiguity is solved for integers, the receiver switches in the so called "on-the-fly" mode and the user's position can achieve centimetre-level accuracy. From this moment on the user's receiver has just to monitor the quality of the estimated phase to detect the presence of cycle slips that corrupt the measurement, but the ambiguity resolution has not to be performed anymore, provided that the phase tracking is not interrupted. This

process keeps valid until a signal blockage forces the PLL to lose the lock. If so, the process needs to be restarted to fix a new value of the ambiguity.

5.6.2.2. Performance of RTK with high end receivers

Today RTK allows for improving the accuracy of the estimated position down to centimetre-level. Typical values of the mean error on the North, East and vertical coordinates are 1.5 centimetres, provided that:

- the baseline is within 10 Km;
- the base and rover use dual or multi-frequency receivers that perform carrier based measurements;
- the rover is static;
- the antennas have stable phase centre
- the receivers feature multipath mitigation capabilities;
- there is a good visibility of the satellites.

Table 5.2 reports in the third column a typical user equivalent error budget for a carrier-based, dual frequency differential GPS, considers a baseline of 10 km¹⁵. The table also reports the error budgets associated to other types of signal processing for comparison¹⁶.

One Sigma error [m]			
Error source	Code-based, dual frequency standalone GPS	Code-based, single frequency, differential GPS (baseline 50 km)	Carrier-based, dual frequency, differential GPS (baseline 10 km)
Ephemeris	2.1	-	-
Satellite clock	2.1	-	-
Ionosphere	1.2	0.4	0.006
Troposphere	0.7	0.2	0.007
Multipath	1.4	1.4	0.03
Receiver Noise	0.5	0.5	0.01
Total rms	3.6	1.6	0.034

Table 5.2: Typical error budgets for different types of signal processing.

5.6.2.3. First results of RTK with low cost receivers

The results of the tests in [RD100] demonstrated that the performance of standalone GNSS receivers with default settings were clearly above the meter level (i.e.: Horizontal positioning error in the range [1.3 – 3.5] m) driving on a beltway with far buildings surrounding the antenna. The error reached dozens of meters in the most constrained environments. This is true either with low cost receivers or with geodetic-grade equipment. These results underline the difficulty in performing satellite-based navigation in the urban environments.

Second, the direct application of RTK algorithms on top of carrier phase measurements at the output of the low cost receiver (combined with a patch antenna) leads to unreliable ambiguity fixing. As explained and well described with appropriated figures in [RD100], the ambiguity

¹⁵ http://gpspp.sakura.ne.jp/paper2005/isgps2008_paper_ttaka.pdf.

¹⁶ http://www.edu-observatory.org/gps/gps_accuracy.html][http://www.gps.gov/cgsic/international/2009/stockholm/emar_dsson.pdf

fixing is unreliable 56% of the time on the beltway and up to 80% of the time in Toulouse downtown. In these cases, the error on the position often exceeded 10 meters. Therefore, the computation of a reliable integer ambiguity is a key point and specific algorithms must be used to weight carrier phase and Doppler measurements, carefully excluding low quality data and detect cycle slips. The risk is to have a RTK receiver with a high rate of incorrect fixes, that is not usable.

[RD100] demonstrated that there are still quite a lot of challenges to reliably use precise positioning in difficult environment. The major challenge seems the availability of carrier phase measurements, that remain fragile, whereas the code pseudorange measurements, used as references for fixing carrier phase ambiguities, can still be affected by strong errors due to multipath or Non-Line-of-Sight (NLOS) tracking. However, the same paper proposed a RTK solution based on Kalman filtering using code, phase and Doppler measurements, a careful cycle slip detector and corrector, and a **heavy measurement selection**. It was based on a low cost platform (i.e.: < 100 \$) with a GPS/GLONASS single frequency receiver and a patch antenna.

Table 5.3 reports same of the values presented in [RD100].

Filter method		Urban – HPE (68 th percentile)	Beltway – HPE (68 th percentile)
Test #1	Baseline RTK filter	2.56	1.67
	Advanced filter, with improved measurement section	1.60	0.13
Test #2	Baseline RTK filter	2.19	1.41
	Advanced filter, with improved measurement section	1.52	0.08

Table 5.3: Horizontal Position Error reported in [RD100].

These results show that:

- In a “semi-urban” environment, such as the beltway, it was possible to solve the integer ambiguity and compute precise positions for about 70 % of the time, that in turn resulted into a positioning error lower than 10 cm.
- In urban, it was possible to solve the integer ambiguity and compute precise positions only for less than 20 % of the time. However, the proposed algorithms, designed to carefully select/weight measurements and detect multipath, improved the positioning accuracy, whose 68th percentile was about 1.5 m.

5.6.3. TECHNOLOGICAL ISSUES FOR PRECISE POSITIONING FOR ROAD USERS

This section discusses some technological issues to overcome before applying precise positioning in road. They arise from two facts: first, the state-of-the-art architectures are expensive in terms of equipment and access to the service; second, they cannot be directly applied to any road scenario, because the non-open-sky and highly variable visibility typical of the urban situation prevents in practice the use of technologies expressly developed for open-sky operations. These reasons pushes the current research to look for affordable solutions able to overcome the current barriers mentioned above. The challenges faced by the current research are discussed hereafter.

First, the **trade-off between cost and performance**: so far, PPP has been a technology for professional applications, which require the highest possible accuracy and are available for paying for it. For this reason, dual-constellation and dual-frequency receivers with professional antennas have been the common, though expensive, choice for the employed equipment. Nonetheless, PPP with single-frequency receivers has received increasing attention because of the opportunity it can offer of reducing equipment costs (as well as performance) [RD101][RD102][RD103][RD104]. Indeed recently, service providers have started widening their offer with cheaper single-frequency PPP equipment with medium-level accuracy, for less-demanding applications.

Second, the **development of a suitable user equipment**. The *equipment quality* is indeed responsible for the ultimate performance of the positioning estimation, besides any external information. The following aspects play a role in the quality (and cost) of the equipment:

1. It has been demonstrated that the quality of the antenna matters [RD98][RD105][RD106]: in the case of a low-cost antenna, there is no control on the variation of phase centre of the antenna, which biases carrier-phase measurements. In such a case, ambiguity resolution is more difficult and takes longer time. Furthermore, extremely-low-cost antennas for personal mobile devices (e.g., smartphones) cannot suppress multipath and experience quite irregular gain patterns, even worsen the quality of the received signal.
2. The quality of the range measurements produced by the receiver should be good enough to employ carrier phase-only ranging techniques and exploit their fine resolution. It means that tracking loops must be designed and controlled for high stability, low cycle slip probability and tracking robustness against multipath and signal fluctuations [RD98], that are likely in urban contexts
3. In the case of real-time applications based on PPP, the receiver must be able to retrieve (i.e., downloading from the Internet or receiving an ad-hoc radio message), decode and correctly apply the PPP corrections, including those specifically needed for non-differential processing. Furthermore, it must be smart enough to apply adequate signal selection strategies to exclude from the PVT solution all degraded satellite signals without penalizing too much the visible constellation [RD98]. On the other hand, in the case of non-real-time processing these operations are demanded to a remote server which executes post-processing, typically at the end of the mission. In such case, the receiver must collect and store (or send) its measurements to the remote server, which then computes the precise positions covered by the receiver.

Furthermore, the type of the environment surrounding the receiver directly impact the performance of the methods used for precise positioning. In some cases, **the environment can pose a barrier difficult to overcome**. In fact, as already said, carrier-phase processing is based on two mandatory assumptions: (i) no cycle slips occur inside the phase synchronizer in the observed time interval, and (ii) there is no loss of lock of the phase synchronizer to the received carrier signal (i.e., the ambiguity term does not change). Of course, if these requirements deserve the utmost care in open-sky conditions, they become really hard in degraded propagation conditions, i.e., in the case of frequent signal blockages, signal fading, non-line-of-sight and multipath propagation, as it is common in urban environments.

5.6.4. PERSPECTIVES TOWARD THE ROAD SECTOR

Recently, precise positioning methods have been investigated on **"light professional" receivers**, devices which may admit even decimetre-level accuracy for applications that do not need the accuracy provided by survey-grade receivers, but that require better performance with respect to consumer grade products, with a price pressure much less extreme than consumer products [RD107]. Following [RD107], such kind of applications might be for example agriculture and trains. However, we believe that also other applications in the road domain (e.g.: precise navigation of vehicles for road maintenance) have the

potential for being classified as “light professional” as per the given definition. We exclude the use of light professional receivers for personal leisure or navigation where the current accuracy is normally perceived as satisfactory enough not to spend more money for improving it [RD107].

The major barrier for the use of carrier-phase measurements is the requirement for continuous and precise phase tracking. This can be done in receivers which implement continuous carrier tracking loops (i.e., some smartphone-grade receivers must be excluded [RD70][RD71]), techniques for multipath mitigation, and cycle slip detection and correction. Furthermore, dense urban environments could really deteriorate the achievable performance, but the advent of new constellations, and therefore the availability of more satellites in view, will improve the continuity, as recently demonstrated by [RD98][RD93][RD108].

Taking these considerations in mind, it is possible to argue that **the penetration of precise positioning in the road sector is on its way**, although with a likely different flavour with respect to the classic approaches popular in geodesy, survey and precise machine guidance. The principal aspects that could characterize this new market entry are arguable as follows:

- First, it can be expected that road-domain applications require “several-decimetre”-level precision instead of sub-centimetre-level. This would relax the accuracy requirement with an immediate impact on the equipment complexity: single-frequency receivers could emerge in the market, enabled with a medium-complexity PPP signal processing software and equipped with high-level (though not top-level) antennas. A relaxed requirement in terms of positioning accuracy would also allow dramatically reducing the convergence time, one of the major drawbacks of PPP.
- The cost for such a “low-complexity” PPP receivers can be expected to be more affordable than current PPP-enabled devices available today on the market. From some perspectives, this fact could help the market penetration [RD109]; on the other side, a cost reduction down to a “mass-market” level cannot be reasonably expected in the short/medium term. Therefore, the first PPP penetration may be expected in *professional* applications related to the road domain (e.g., precise navigation of vehicles for road maintenance), where a clear *economic* revenue for the investor justifies the sustained costs.
- The main advantage of PPP with respect to RTK is that it provides a global and absolute positioning and timing service without the need of nearby reference stations. Long converge time is a drawback mainly if centimetre levels accuracy is targeted. Observing current trends and advanced of the PPP technology in the last decade, we believe that PPP services for road applications will become common in the next future.
- The poor performance of algorithms for carrier-based ranging in degraded environments is still an open issue. Although it can be mitigated with multi-constellation coupled with ad-hoc processing, this approach is not at the state-of-the-art and likely deserves further studies and validations. The development of receiver-side techniques able to mitigate such problems is an open research topic, as witnessed for example by [RD98]. For these reasons, the earliest applications should be likely expected limited to open-sky (or mostly-open-sky) situations, such as motorways in rural environments, airports, large parking areas, etc.

Criteria	Score	Justification
Performance		
Accuracy	H	Methods for precise positioning, either PPP and RTK, can be applied on top of measurements taken with low cost GNSS receivers, drastically increasing the positioning accuracy that can reach centimetres-level. At the time of writing this is a hot research topic, raising interest in the road domain.
Availability	L/M	A major drawback of carrier-phase positioning in road is the availability of carrier phase measurements, that remain fragile in urban contexts. In environments characterized by narrow streets with high building surrounding, it is still not possible to fix the carrier phase ambiguity most of the time. It is expected a tremendous benefits with new constellations.
Continuity	L	In urban, obstacles and buildings can obscure the LOS signals and break the carrier phase measurements, that in turn result into a loss of continuity of carrier phase positioning.
Maturity		
Technological readiness	L	Results obtained processing data sets collected in a real environment, but at a proof of concept level.
Time-to-market	M/H	Since the technological readiness associated to PPP and RTK with mass market receivers is considered low, the time-to-market is supposed long. However, the availability of new satellites from new constellations will encourage the research on this topic, as it will increase the possibility to use carrier phase measurements for precise positioning also in challenging environments. This is valid either for PPP and RTK.
Cost		
Estimated cost in 2015 (current)	L/M	N.A
Estimated cost in 2025	L/M	The major barrier of this application seems the poor availability of carrier phase measurements and the need of rather complex algorithms for the selection and filtering. However, it is reasonable to think that the costs associated to this technology, once the algorithms will be assessed, will be negligible with respect to current solutions.
Challenges		
Technological challenges	M/H	<p>The availability of carrier phase measurements is essential for precise positioning. The road environment corrupts such measurements, so that it is necessary to filter and carefully select measurements before performing RTK and PPP. Such filtering and selection processing is rather complex and is associated to a high computational burden. Alternatively, more robust carrier phase tracking loops should be designed.</p> <p>The quality of the antenna, with a stable phase centre, is also required. Most of the antennas used today in road application do not feature such stability and cannot be used when combined with precise positioning methods.</p>

5.7. ADVANCED DIGITAL MAP MATCHING

In strongly constrained environments, like city centres, the propagation phenomena in the surrounding of the antenna, more precisely diffraction and multipath, are responsible for severe errors on the raw observables (pseudo-ranges and Doppler measurements) that are measured by the receivers. The most severe deviations (up to several tens of meters) may occur in case the reflected path is the only tracked, whereas the direct one is blocked. Such signals are called Non-Line-Of-Sight (NLOS) signals.

A standard low-cost receiver, with no particular knowledge of the environment, acts blindly when computing the navigation solution from the raw observables. It may filter the observables output by the satellite signal tracking process according to the signal-to-noise ratio (SNR) or possibly according to the elevation angle. But mainly, since it gives greater place to continuity and availability compared to accuracy, it will use most of the measurements even if the latter are strongly corrupted by propagation phenomena.

When some a priori knowledge of the environment is embedded in the receiver, for instance under the form of a digital map with building height information, the processing (and resulting accuracy) of the navigation solution can be significantly improved because the conditions of reception of each signal can be characterized. The level of characterization depends on the accuracy and completeness of the map, and on the computation power one can use for this purpose [RD112].¹⁷

Digital maps with 3D data proved to make it possible the determination of NLOS satellites in real time and obtain significant benefit in terms of navigation accuracy. However, such data are difficult to handle with Geographical Information System (GIS) embedded software in real time.

State-of-the art map matching is based on the principle of computing the distance between the estimated vehicle location and the nearest road segment of a digital map [RD113], in which roads are represented by one or two polylines (depending on whether lanes with opposite driving directions are physically separated), i.e., a series of nodes and shape points, connected by segments. A review of the current map-matching algorithms for transport applications can be found in [RD32]. More recent works [RD114] [RD115] [RD116] propose to solve the positioning problem with the digital map constraints using a particle filtering in which the particles leaving the road are eliminated.

In the last years, researchers have addressed the use of 3D models of the environment to analyze the conditions of reception and mitigate multipath phenomena. 3D map data were introduced in the positioning problem by [RD117], where a detailed LOS-NLOS visibility boundary is generated by ray-tracing from (and around) the a priori receiver location. The underlying idea is to separate the satellites which are in direct visibility from the ones which are hidden or in indirect visibility. Several other similar approaches have been proposed, for instance [RD118] [RD119] [RD120] [RD121], in which the integration with motion sensors and/or road map constraints are used to improve the final accuracy performance, without affecting too much availability. In addition to the aforementioned techniques, "shadow masking" was introduced by [RD122] and seems to bring additional interesting information. Last, [RD123] models a path delay for NLOS, in order to compute and apply a corresponding range correction directly.

¹⁷ A different a-priori knowledge of the surrounding environment can be obtained through the use of visual sensors, as discussed in Section 5.3.1.3.

5.7.1. TECHNOLOGICAL ISSUES FOR ADVANCED DIGITAL MAP MATCHING

At the time of writing, the use of advanced 3D digital maps has been investigated mainly in **research works** and demonstrated in some very heterogeneous field tests. For this reason the maturity of the advanced digital map technology to improve GNSS accuracy should be considered still low.

The main issues associated to the described approach are related to the availability of the advanced digital maps (construction, installation and processing on board of the receiver device, update, data format) and to the risk of reducing the availability of the positioning service although improving the accuracy. These issues are well argued in the promising work [RD112]:

- Advanced digital maps: The additional data included in a digital 3D map are difficult to handle in real time with GIS embedded software, due to the high volume of data to be stored and the moderated processing capabilities of the in vehicle embedded systems. Therefore the information contained in the map should be designed as simple as possible, so that it matches the requirements of usual embedded and navigable maps. This should actually be registered as a set of attributes applicable to the standard polyline structure of 2D digital maps [RD112].
- The construction of such maps is another issue: they are available, not for free, for some city centres, but it seems that no standardized data formats for this kind of applications have been agreed. Therefore applications must be tailored to proprietary maps and formats, possibly not optimized for the purpose of this application. Furthermore, the advantage of such methods is strictly related to the update of the map, meaning that it reduces with non-updated maps.
- Availability of the accurate fixing. The exclusion from the navigation filter of the satellites in NLOS increases the position accuracy, but is likely it poses a problem of availability. Indeed, without additional sensors (i.e.: inertial or motion), the number of LOS pseudoranges could be often less than four in urban scenarios, preventing the position fix computation. The work [RD112] experimentally demonstrates that the median of the positioning error can improve from 40% to 70% using LOS satellites, with respect to a standard solution that takes all the tracked satellites. However, with the LOS only the availability of the final position has dramatically decreased, since a positioning solution has been computed for only 70%-80% of the total number of epochs, against almost 100% with all satellites. With a mixed solution, where NLOS satellites data are progressively re-introduced in order to avoid unavailability, the number of position fixes raises again to almost 100% at the cost of a reduction of the accuracy improvement to 30%-65% [RD112].

5.7.2. PERSPECTIVE TOWARD THE ROAD SECTOR

Leveraging on the progress of the technology for data computing, 3D maps will be a mean to improve the position accuracy provided by standalone GNSS receivers. Multi constellations are an advantage for the integration of GNSS with 3D maps, because they smooth the risk of reduced availability after the filtering of NLOS measurements. Despite these advantages, the current level of maturity of this technology seems not ready to support new products in the short/medium term.

Criteria	Score	Justification
Performance		
Accuracy	M	Improved accuracy thanks to NLOS error mitigation. Expected still at the meter level (although a clear and stable characterization is not available yet) Associated risk of reducing the availability of the positioning service in urban scenarios when measurements are filtered and LOS only measurements are used
Position Integrity	L	Risk of reducing the availability of the positioning service in urban scenarios when LOS only measurements are used
Maturity		
Technological readiness	L	Several proposals, but all at the level of research work (with demos)
Time-to-market	H	Barriers can be seen in the difficulty in handling 3D maps in real time and in dealing with non-standardized data formats. Furthermore, the availability of 3D maps is not worldwide guaranteed
Cost		
Estimated cost in 2015 (current)	N.A.	N.A.
Estimated cost in 2025	N.A.	N.A.
Challenges		
Technological challenges	M	Availability and handling of 3D maps Maturity of the proposed approaches
Framework conditions		Lack of standardized map data format tailored for the specific application

6. CONCLUSIONS AND RECOMMENDATIONS

A revised version of Table 4.4 in Section 4.3 is reported at Page 77 (Table 6.1), listing the potential technological enablers able to achieve the expected positioning performance features. Such a revised table aims at summarizing the major results, pointing out some final considerations.

The added value of Table 6.1 is represented by an “*overall evaluation score*” assigned to each technological enabler with respect to a specific positioning performance feature. This is the outcome of the investigation of each technology, as a synoptic view of the tables at the end of each subsection of Section 5.

In particular, the overall evaluation score in Table 6.1 is simply provided with a coloured tick, being:

- **green** → a technology that allows to effectively support the specific performance feature, without significant technological barriers to be overcome towards a short-term full readiness¹⁸;
- **yellow** → a technology that either is not able to provide a full achievement of the expected performance, or its short-term adoption is prevented by some barriers (e.g. a low TRL or a significant cost);
- **red** → a technology that is not considered able to achieve the expected positioning performance.

Looking at the content of Table 6.1, the following considerations can be derived:

- A number of technologies supports the “**position accuracy**”, even if with different level of effectiveness and maturity. Among them, the multi-frequency receivers and the GNSS/IMU tight integration appear to be the most ready-to-market, but with potential accuracy not less than a few meters. An effective support to a higher accuracy is allowed by precise positioning techniques such as PPP and RTK with “light professional” GNSS receivers: however, even if a topic raising interest in the road domain, the precise positioning techniques are still a research topic.
- The “**position authenticity**” appears to be effectively supported by a number of different and complementary technologies. If some of such technologies are somehow related to GNSS (e.g. the signals authentication ensured by Galileo through the use of multi-frequency receivers), it is worth noting the role of non-GNSS solutions, i.e. the integration with SoO, in cross-checking the position authenticity. However, these non-GNSS solutions are not originally conceived as authentication methods, then some efforts shall be devoted to make them effective (for instance, the development of proper algorithms aiming at check the position authenticity leveraging the SoO features).
- Also considering the “positioning authenticity”, it is worth mentioning the different stage at which the different available technologies are effective: the GNSS signals authentication is the only method that can ensure *a priori* authenticity of the position, while all the other solutions can only support *a posteriori* check of the authenticity then enabling a detection function.
- Concerning the “**robustness to interference**”, a quite limited set of technologies seems to be available among those analysed. While the use of multi-frequency receivers, exploiting their inherent frequency diversity, and the implementation of a GNSS/IMU tight integration can be considered ready for the market, the integration with SoO (e.g. digital TV and cellular network signals) is subject to a joint regulation with standardization

¹⁸ It is worth mentioning that, even if each technology has been also analysed in the perspectives of the road sector and the outcomes of this analysis is considered in formulating the overall evaluation score, “readiness” has to be intended here from a purely technological point of view. As a matter of fact, the adoption in the road domain of a specific technology may be driven by other opportunities.

bodies. In addition, the proper algorithms to exploit the benefits of such an integration for interference mitigation are not state of the art.

- Any time GNSS receivers are combined with inertial sensors or augmented with terrestrial navigation technologies (i.e.: DVB-T and cellular networks), there is an inherent improvement of the **availability**. This because in case of short/medium GNSS signal outages, the PVT data can be provided by non-GNSS means.
- Focusing on the rows of the table, it can be noted that the technologies supporting the "position accuracy" (e.g. the GNSS/IMU tight integration) are also effective in terms of "**position integrity**". In fact, more accurate position estimation may result in a better protection level, then broadly speaking, increasing the positioning integrity.

In conclusions:

- Even if not yet state-of-the-art in the GNSS-based positioning in the road domain, the implementation of a GNSS/IMU tight integration represents a cost-effective solution able to support most of the performance features (e.g. accuracy, authentication, integrity), especially if complemented with multi-frequency receivers;
- The precise positioning techniques (i.e. PPP and RTK) on top of measurements taken with mass market GNSS receivers come with a quite low TRL today, but the availability of new satellites from new constellations (e.g. Galileo) will encourage the research on this topic, as it will increase the possibility to use carrier phase measurements also in challenging environments like urban.
- When available (e.g. vehicles equipped with a dedicated OBU as for the DSRC), the SoO may represent a good solution in complementing EGNSS mostly for the purposes of position authentication, since they are non-GNSS technologies. Their contribution for other features is not yet mature, but DSRC – as soon as some limitations in the quality of measures will be overcome - appears a promising technology to look. In theory, DSRC-based positioning modules enable cooperative positioning, that in turn may increase the position accuracy. This is a potentiality also fostered by the foreseen significant penetration of such technology, now driven by road rolling needs.
- The added value provided by the current non-GNSS sensors (low cost, but low performance) is very limited. An effective support to the positioning performance, accuracy at first, is expected from high-end sensors, but comes with medium-high cost. For this reason, such sensors are expected in the short/medium term for specific demanding applications such as the autonomous driving.

PERFORMANCE FEATURES TECHNOLOGICAL ENABLERS		Position accuracy	Time accuracy	TTF	Position authenticity	Robustness to interference	GNSS sensitivity	Availability	Position integrity	Continuity
Multi-frequency receivers	Sect. 5.2	✓	✓		✓	✓			✓	
Combination of GNSS receivers with vision sensors	Sect. 5.3.1	✓						✓		✓
Tight integration with IMU	Sect. 5.3.2	✓			✓	✓		✓	✓	✓
Civilian GNSS signals authentication	Sect. 5.4.2				✓					
GNSS spoofing countermeasures	Sect. 5.4.3				✓					
Integration with SoO – DVB-T	Sect. 5.5.1				✓	✓		✓		
Integration with SoO – Cellular networks	Sect. 5.5.2			✓	✓	✓	✓	✓		
Integration with SoO – DSRC	Sect. 5.5.3	✓			✓			✓		
Precise Positioning – PPP	Sect. 5.6.1	✓	✓						✓	
Precise Positioning – RTK	Sect. 5.6.2	✓	✓						✓	✓
Advanced digital map matching	Sect. 5.7	✓							✓	

Table 6.1: Overall evaluation of the identified technological enablers for the performance features.

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