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Indoor Positioning with
GNSS-Like Local Signal Transmitters

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1. Introduction

After more than ten years of research into indoor positioning and localisation techniques, whose aim has been to provide real continuity of service, as with GNSS outdoors, one has to conclude that no solution has yet been found.

1.1 A very brief history

The real story started a little bit more than ten years ago, in the context of the Galileo project, with the very interesting idea of the so-called "*local elements*". The question was to do better than the future competitor GPS in designing a real positioning service for the twenty first century: technology transparency to the end user, simple and intuitive operation, performance and of course continuity of the positioning in all possible environments that the modern citizen will face with his/ her mobile phone.

One technology followed another: Ultra Wide band (UWB) was the first candidate, at the end of the 20th century. But, facing the problem of considering the proposed approaches as a real "*indoor GPS*", Assisted-GPS (A-GPS, shortly followed by the Assisted-GNSS) was the next one, typically between 2003 and 2007. It was at that time that the positioning community seemed to realise that the problem was really hard and that a huge research effort would be necessary. For instance, this was the time that ubiquitous positioning was no longer described as imminent and works being carried out in many directions now had a chance to be heard. A few industrial partners, often small organisations, proposed various technical solutions, from the well-known WiFi to the use of TV (television) signals for example.

On the other hand, the market of "*Location Based Services*" developed very slowly, probably due to the complexity and diversity of the environments to be addressed: "one" is still waiting for THE FREE technological solution (as in the case of GPS : this system is one example of the numerous modern "costly free" services) (Kupper 2005). Current techniques proposed in order to provide this continuity of service are mainly oriented, for commercially available solutions, towards WiFi. Some R&D partners also propose inertial sensors or vision based approaches.

1.2 Applications and services

The potential applications and services likely to use such ubiquitous positioning systems are numerous. Of course, the first kind is clearly related to guidance and navigation, as currently for outdoors and GNSS related services, which is the natural extension of the most popular applications. But now that the citizen is considered, through his/ her mobile phone, the new services are not only individual (same as the car navigation system, designed for a single user), but also for the community with, for example, the "group" approaches developed by so-called social networks. There is probably a historical parallel that can be drawn between the introduction of the portable clock, about two hundred and fifty years ago, and the development of the navigation capabilities: from individual to collective and from collective to individual. Maybe the advent of these ubiquitous positioning devices will lead to social transformations similar to those induced by the portable clock … but this is another story. Note also that for these collective approaches, telecommunications systems are required (and in that way, this is now probably the "right time"): this is evidence that the two domains, telecommunication and positioning, are so closely linked. Another very important point to consider, when addressing the mobile phone of a user, is that there are then no constraints on the displacements of the citizen (as was the case for a car for instance) and that current positioning devices, namely mainly GNSS ones, are placed in far more difficult environments and uses (this latter point is the most important for the discussion): thus, new techniques, new devices and new services must be imagined and designed.

It is also possible to cite the classical asset management and various surveillance applications, but which must now work in many different environmental conditions. Once again, the individual and collective approaches are one of the important new features. Multimodal transportation, a desire not yet realised, of a world that would like to be able to reduce its energy consumption, clearly needs the ability to position in real-time all the actors and the various components: pedestrians are indoors more than seventy percent of a typical day and are in constant mobility (and in addition have a potential problem of energy), when vehicles will have to be precisely monitored in order to manage not only their locations, but also their energy, their availability, their reservation, to check the payments, etc. Self-service car locations or co-driving applications fit naturally in this same category.

In a totally different domain, certification and security applications can be envisaged on a geographical basis but ubiquity must be reached (current performance of GNSS are not enough). Following the privacy issues, the conditional liberty of prisoners could be largely extended: currently, due to the limitations of positioning systems (coverage indoors), the prisoners are not allowed to take the underground for example (at least in France). The large scale deployment of ubiquitous systems could allow substantial improvements of the capabilities.

The next generation of applications could be in the domain of social networks. The developments of these networks have been huge and the permanent exchanges between people and connected groups are enhanced when geographical data are associated. Note that our imagination could easily apply this approach to objects, of course.

1.3 The main radio based approaches

In terms of technologies for indoor positioning[1], numerous candidates are almost available, some of them being proposed as commercial products and solutions. A fundamental point to understand is that one is always looking for a positioning system that is globally the continuation of GPS in all environments, i.e. a few meters of accuracy, free for the users and with no specific infrastructure to be deployed by any commercial operator. Hence the various directions of works carried out in recent years: indoor GNSS through Assisted-GNSS, although this is not a solution to the problem (see the first lines of this sections), WiFi because one considers that the required infrastructure will be deployed anyway for telecommunication purposes[2] and inertial approaches that really don't need any specific infrastructure. The accuracy being sought eliminates candidates such as the GSM (Global System for Mobile) or UMTS (Universal Mobile Telecommunications System), whatever the technique envisaged.

Among a few others, it is possible to list the following global categories:

- Wireless Local Area Networks (WLANs, such as WiFi) or Wireless Personal Area Networks (WPANs, such as UWB or Bluetooth) based: the main idea is to use these telecommunication networks for positioning purposes. The main problems for translating the GNSS time of flight measurements lie in the non-synchronised nature of these networks and the complexity of the indoor propagation environment. Thus, the usually implemented technique is based on so-called fingerprinting, described in the next section. An exception to this rule is the Ultra Wide Band that fundamentally works in the time domain, thus could potentially allow us to carry out time measurements. Technological developments are still on-going and initial promises have not yet been met.
- Wireless Mobile Networks (such as GSM or UMTS). The use of mobile networks leads to the same basic difficulty as WLAN or WPAN. Although non-synchronisation is a problem, propagation characteristics are probably the largest difficulty. Performances are not at a sufficient level in order to allow a real continuity with outdoor GNSS. Nevertheless, some services are available which implement the so-called Cell-Id (Identification of the telecom Cell the mobile is associated with). This technique allows a mobile terminal to know the area it is in by analysing the base station it is associated with. The accuracy is rather poor, ranging from a few hundreds of meters in densely populated areas to several kilometres.
- Inertial systems have typically three problems: time related shift of the accuracy, distance related shift of the accuracy and the cost of the terminal. Recent smart phones have embedded inertial sensors but positioning remains a challenge. Nowadays, techniques are mainly oriented in two directions: integration of the measurements provided by the sensors (accelerometers, gyrometers and magnetometers) or modelling

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[1] Note that indoor positioning is seen as the ultimate difficulty in order to cope with ubiquity since this seems to include all the most difficult phenomena. This is of course not the only environment where GNSS are not very efficient: so-called urban canyons are also important to be dealt with. Nevertheless, the topic of this chapter is clearly limited to indoor techniques.

[2] This assertion is not 100% right with current proposed solutions since it is almost always necessary to distribute additional access points to existing networks in order to create the required redundancy.

the walking of an individual based on the detection of some very specific instances, such as the precise time the foot touches the ground. Then, the method consists in counting the number of footsteps. These approaches are not yet mature for mass-market applications but research is still being carried out.

- GNSS based systems. In addition to Assisted-GNSS, which is once again not a solution for ubiquitous positioning, the following sections will deal specifically with this problem. Various approaches have been proposed with rather good accuracy results: the remaining problem is clearly the need for an additional infrastructure that needs to be deployed locally. Operators are not ready for this and although very good results are reported, very few systems are really available.

The last category is related to sensor networks. Many systems have been proposed in the last fifteen years, but the lack of standardisation and the high number of sensors that need to be deployed are currently a real drawback.

1.4 The perceived and real needs

If we take a little break to try to analyze the needs (i.e. requirements) for the continuity of service definition, it will quickly become apparent that it greatly depends on the targeted applications and services. But if you ask anybody, the answer will very often be given in terms of positioning accuracy, availability and latency: it should be accurate to better than one meter, available everywhere and instantaneously in real-time. Curiously, the fact that it should be available in three dimensions will almost never be mentioned. Although it really depends on the application (the requirement is not the same for the guidance of a robot in a nuclear reactor and for finding the nearest restaurant), one should be able to distinguish between the positioning "engine" and the resulting services. For instance, GPS does not provide a one meter positioning everywhere, even outdoors, but car navigation systems are very accurate for the delivered service, thanks to map matching and Kalman filtering. The same should apply to ubiquitous positioning. Nevertheless, a good rule of thumb could be to consider that the major difference, in terms of environments, between outdoors and indoors is that indoors is typically a 3D environment, thus requires full 3D positioning capabilities. In that sense, the accuracy should probably be enough to allow the floor level to be determined, i.e. an accuracy of typically half the height of a given floor. In most buildings this means roughly one meter.

Following this general presentation of the indoor field, this chapter is going to focus on radio positioning solutions, and more specifically on GNSS-based radio approaches. The second paragraph is dedicated to an introduction to radio positioning. It is followed by three paragraphs dedicated to GNSS-based architectures: pseudolites, repeaters and repealites. The chapter ends with a synthesis and some hints for the possible future, as seen by the author.

2. The concepts of indoor positioning using radio transmitters

Not all the techniques proposed have, of course, been based on radio techniques, but they are the most important ones for two main reasons: their level of development and maturity on the one hand and their ability to "cross" or to "get around" obstacles such as walls, furniture or people on the other hand. Optical based techniques, like laser based distance

measurements or vision based (camera) scene analysis systems present some real advantages in terms of measurement accuracy (a few millimetres for the former) or orientation determination (very useful for any guidance system, available for the latter). Unfortunately, the foreseen use of positioning devices being mainly dedicated to pedestrians in urban environments, optical obstacles are numerous. These latter techniques are then considered as potential hybridisation[3] candidates. Many types of sensors have also been studied for positioning, such as infrared or ultrasound. Once again, although accuracy can reach centimetre values, the environmental constraints are not compatible with the ubiquitous systems being sought. Another category is, of course, inertial systems which could be a valuable alternative to radio systems: time and distance associated position drifts are not yet sufficiently mastered and the given positioning is relative[4], which means the need for "something else" in order to provide the user with an absolute location. The object of this section is to focus on radio based approaches.

2.1 Measurement techniques

There are mainly four techniques that are used for radio positioning. In fact they come from the history of mathematics and have been improved over the centuries, thanks to the development of instrumentation (Samama 2008). In chronological order there are *angle measurements*, *fingerprinting, time of flight measurements* and *cell-id*.

Angle measurement is the basis of triangulation used by geodesists for measuring the earth. For positioning purposes, the technique is a little bit different and is illustrated in figure 1. The main idea is to measure the absolute direction of a signal received from a transmitter (at the mobile terminal). The reference usually used is the magnetic north which can be obtained from a compass. Thus, with a single measurement, the terminal knows that it is somewhere on the line L1 (see figure 1). Of course, this is not accurate enough, so it is necessary to carry out a second measurement from another transmitter, say T2. This second measurement allows the terminal to know that it is somewhere on line L2. The combination of both measurements gives the location of the terminal, at the intersection of lines L1 and L2. This kind of approach, combining multiple measurements in order to find the location geometrically, is often applied. Two measurements give a location in two dimensions.

This technique can be applied in 3D but requires a 3D angle measurement, hence two angles (azimuth and elevation): this is possible with 2D receiving antennas. Two 3D angle measurements, hence four angles, lead to a location in 3D. Note that when, in 2D, three measurements are available, there is the need for an additional method in order to determine the location considered, as can be seen in figure 1 (right). In the present case, it is often chosen to consider the centre of the inner circle of the triangle that is formed by the intersections of the three lines.

This technique can be quite efficient since angle of arrival measurements are usually based on phase differences which can be measured with rather high precision. Unfortunately, in

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[3] Hybridization is the approach that consists in coupling two or more techniques in order to provide the device with improved performance, either in terms of accuracy or in coverage or availability.

[4] Relative positioning refers here to a position that is given with reference to the previous one. Thus, there is the need to know the first position in order to be able to give an absolute positioning (given in a known reference frame).

indoor environments, the difficulty comes from the fact that the propagation is characterised by a large number of reflected path (from walls and all reflective objects), called multipath. Those multipath are even sometimes more powerful than the direct signal, which can in turn also be absent. Thus, even if the angle measurement is accurate, the environmental conditions are likely to mislead the positioning algorithms.
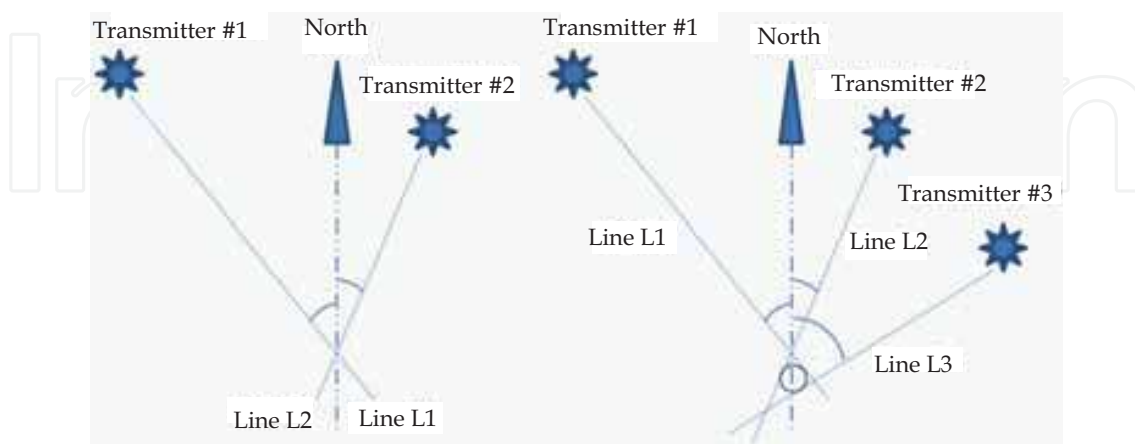

Fig. 1. Angle measurements

The second technique is called *fingerprinting*. The first idea of this method was reported around the sixteenth century when a solution to the longitude problem was being sought. Some scientists had the idea to make a complete geographical cartography of the magnetic field of the earth: if there is a unique link between the location on earth and the value of the magnetic field, then one can consider that the magnetic field value is a perfect indicator for finding a location. Unfortunately, the magnetic field is not a good candidate for such a purpose. This idea came back to engineers with the development of wireless networks: the complexity of the indoor environment for propagation led to the revival of the fingerprinting approach: the received power of the radio signal is now the physical value that is measured. The indoor environment is then cut into squares and the fingerprints (the received power) measured at each intersection of the grid (see figure 2): the "map" associated with transmitter #1 (a data base indeed) is created. The problem is now that many different fingerprints are identical for different locations. The method of multiple measurements is once again implemented: in this case, a second (and more, if required) transmitter is added and a second map is filled in. The location is no longer characterised by a single value but now by a couple of values. In the case of n transmitters, then all calibrated locations are characterised by a vector of length n.

The way in which positioning is then achieved in real-time is quite simple: the mobile terminal carries out received power measurements from all the "radio visible" transmitters in its environment and fills in its own vector. The location is obtained by finding the nearest neighbour in the complete set of maps (data bases) available. The need for this "calibration" phase is clearly a drawback of the method because it is time consuming and, moreover, because it is not a stable operating mode, since the power received is bound to be modified by any movement of any obstacle (including people for instance). Thus, techniques have been proposed in order to manage in real-time (or for longer periods of time) the variation of the maps in comparison with the reference maps. Note also that more measurements should lead to a more accurate positioning.
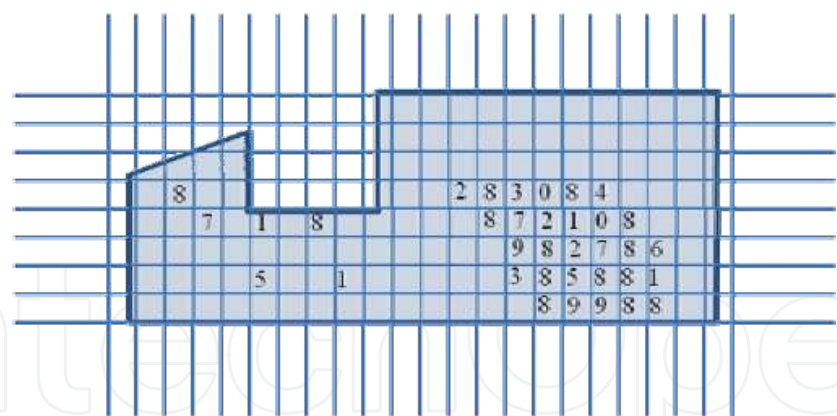
Fig. 2. The fingerprinting approach

Time of flight measurements are quite simple in principle but require acceptable propagation models (Kaplan 2006), (Parkinson 1996). The basic idea, shown in figure 3, is based on the measurement of the time required by a signal to propagate from a transmitter to a receiver. Once obtained, this time is usually converted into a distance. In the case of radio signals, it simply consists in multiplying the time by the speed of light, typically 3×10^8 m/ s. Of course, this model is too simple in real cases, so the modelling of the propagation is an essential step. Once one has the distance between the transmitter and the receiver, it means that the receiver is somewhere on the surface of a sphere whose centre is the transmitter and the radius the above mentioned distance. It appears clearly that this is not enough for positioning. Thus, we use additional measurements in order to reduce, geometrically, the uncertainty. A second measurement from a second transmitter (see figure 3) allows us to reduce the set of possible locations to a circle, while a third one reduces the set to two points and finally a fourth measurement leads to a unique location[5]. In case of more than four measurements, techniques such as least square are usually applied in order to find the optimal location in a set of superabundant equations.
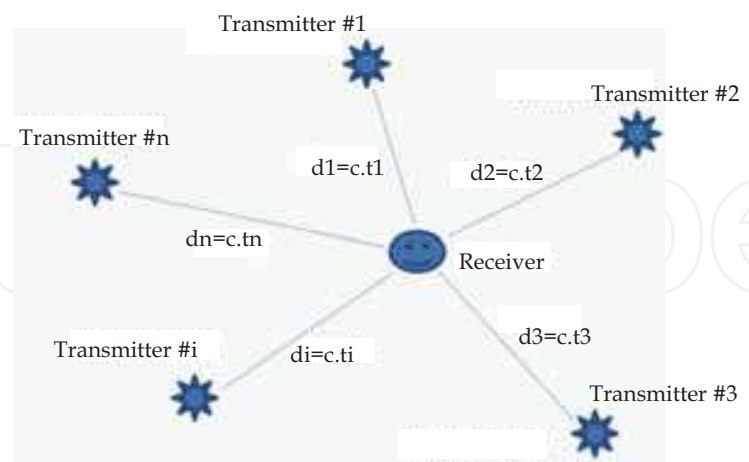

Fig. 3. Time of flight positioning

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[5] Note that here we are dealing with the real world and we know that the location exists. Thus, even if four spheres do not have an intersection in mathematics, we are sure that in the present case they do have one, the location of the receiver. The positioning algorithms must implement mechanisms that are able to obtain such a location even when considering unavoidable measurement errors.

There is a really difficult problem in this time of flight measurements: the synchronisation between transmitters and receivers. There are indeed two different synchronisation problems: the first concerns the synchronisation between transmitters (since multiple measurements are carried out from different transmitters) and the second concerns the receiver with the various transmitters. The two problems are not equivalent since if it is possible (not necessarily simple) to imagine "wiring" the various transmitters, it is often not possible to have a link from the transmitters to the receiver, other than the radio link Radio synchronisation is possible but requires a bandwidth proportional to the accuracy needed. In practice, synchronisation to the nanosecond[6] is not achieved through radio links. In the case of GNSS, this synchronisation is achieved by adding an additional measurement, from an additional satellite, in order to solve this new unknown variable. In previous systems, such as Decca[7], the synchronisation between transmitters and the receiver was not carried out: instead, differences of time measurements from two transmitters were carried out. In such a case, the synchronisation unknown disappears (because of the difference) and the positions of the receiver, characterised by a given difference of flight times, are located on a hyperboloid whose foci are the transmitters. Once again, multiple difference measurements are needed for positioning.

Note that the complexity of synchronisation of radio systems comes from the speed of light. Ultrasound based approaches do not have the same problem since the speed of the signal is reduced by a factor of nearly one million. In such a case, synchronisation to the millisecond is comparable to the nanosecond requirement of the radio system.

For the inter-transmitter synchronisation, two generic approaches have been implemented. The first one uses cables in order to create a real physical link between transmitters: then, a simple calibration phase, once only, is carried out in order to know the exact synchronisation. The second one, implemented in GPS for instance, is to use very slow drift clocks[8] and to carry out a multitude of measurements from known locations in order to inverse the positioning problem and to determine the non-synchronisation variables (one for each transmitter). Of course, this approach is expensive and cannot be followed when designing low cost indoor positioning solutions.

The *Cell-id* approach is the simplest one and does not need any modelling (see figure 4). As a matter of fact, a coverage area is associated with the transmitter, whose shape is usually considered to be a hexagon (of course the actual shape depends highly on the radio environment). When the receiver is "simply" able to connect to the transmitter, one considers that it is within the coverage area. This is a simple way to provide a location. This is not very accurate for high power transmitters that have a wide radio range, but can be very good for very low range devices. Of course, in this latter case, the number of transmitters should be high if one wants a wide coverage. As usual, compromises have to be made.

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[6] One nanosecond at the speed of light is equivalent to 30cm. When a typical positioning accuracy of one meter is wanted, such a synchronization precision is needed.

[7] Decca was a terrestrial positioning system. Propagation models were developed and it appeared that a better performance was obtained over sea rather than over land.

[8] Please note that using atomic clocks is not enough for synchronization purposes. These clocks are used for the low rate of their drift, hence the larger time interval required between synchronization updates.
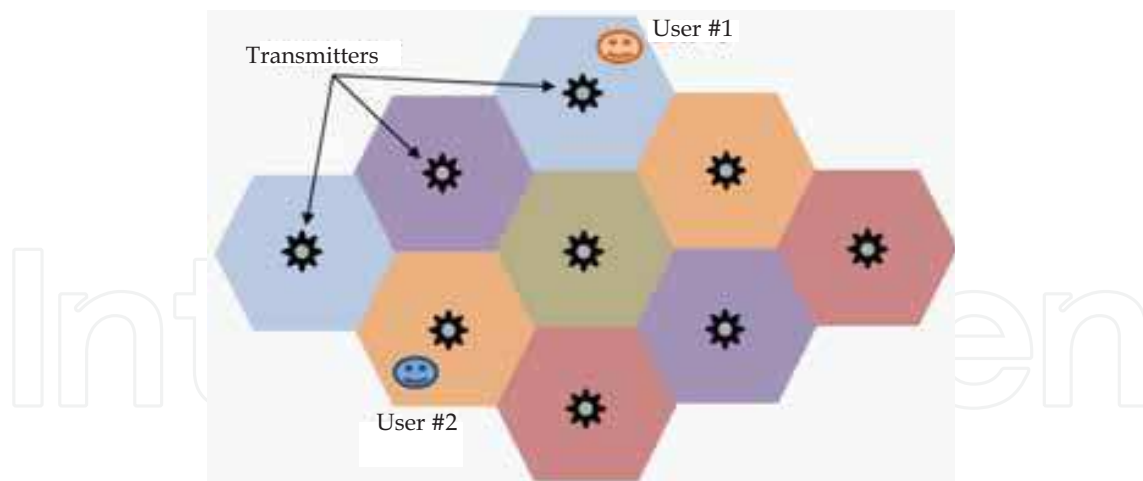
Fig. 4. The cell-id approach

2.2 Main differences with outdoor techniques

Let us come back to the specific case of indoors: some major differences have to be kept in mind in comparison with outdoors. Let us also discuss the case of GNSS since this chapter is dedicated to indoor GNSS-based solutions. First of all, the various techniques are based on time of fight measurements, the same as outdoors, but consider the following parameters for discussion.

- *Propagation environments*: indoors is a very difficult environment and acceptable models are not available. This means that signal processing must solve problems that are either not present, or less difficult to solve, outdoors, the most challenging being multipath. Another problem is related to the possibility of Non Line of Sight (NLOS) path from transmitters to receiver, which happens more often than outdoors. The same kind of techniques could be envisaged but outdoors they are usually based on a certain redundancy of available signals, which is not the usual case indoors.

- *Dilution Of Precision (DOP)*: the geometrical distribution[9] of the transmitters is a very important point to consider when dealing with positioning systems that use distances in order to carry out the calculation. Outdoors, for a location on earth, with GNSS for instance, there is disequilibrium between the horizontal DOP (HDOP), calculated in the horizontal plane, and the vertical DOP (VDOP), calculated in the vertical plane. This discrepancy is due to the fact that when the distribution can be really uniform horizontally (all the satellites being uniformly distributed around the receiver), leading to a good HDOP, this distribution cannot be so good vertically since only satellites above the radio horizon (which is quite similar to the geometrical horizon in the present case) are visible. Thus, the HDOP is usually better than the VDOP. Indoors, things are quite different since one can decide the location of the transmitters: it is very important to locate at least one transmitter below the receiver in order to reduce the VDOP (Vervisch-Picois and Samama 2006). Evaluations have shown a dramatic

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[9] This DOP allows the receiver to give a real-time estimation of the accuracy provided to the user (the User Estimated Range Error in GPS for example): it is of uppermost importance for any application or service.

improvement in the VDOP values, leading to a much better estimation of the user location accuracy.

- *Distances*: indoors, the distances are much smaller than outdoors and new problems arise such as the so-called near-far effect. Depending on the codes that are used (case of GPS), there is a limit of detection of two signals with too high a power difference. The lower one will be undetectable because it is impossible to extract from the noise. Once again, this situation is almost impossible outdoors since the transmitters (the satellites in the case of GPS) are very far from the receiver and the difference in distances from two satellites can reach a maximum of a few decibels only. Indoors, this difference can reach a few tens of decibels: specific signal processing techniques are then required.

- *Initial point in the calculations*. Classical algorithms of calculation of location are based on iterative techniques that require an initial estimation of the user position. In the case of GNSS, only three measurements are necessary for geometrical purposes[10] since the intersection of the surfaces of three spheres gives two points, one of which is above the plane that includes the three centres (the satellites indeed) of the three spheres, the other one being below. When the receiver is on the surface of the earth, only the location that is below the plane is possible: thus, only three satellites are required from a geometrical point of view. Consequently, the initial location estimation is usually taken somewhere on the earth's surface, and this is sufficient. Indoors, the situation is a little bit different since the two resulting locations (above and below the plane) are rather close to each other and the choice of the initial estimation is fundamental in the convergence of the algorithms. Thus, either one chooses to use five transmitters (instead of four satellites) or to keep four transmitters and choose an initial location of the user that is inside the building (which is not such an easy task).

- *Immobility of the transmitters*: in the sky, GNSS satellites are non-stationary. This feature causes some troubles in the way one needs to calculate their locations each time one wants to carry out positioning, but offers some interesting features that are no longer available indoors where transmitters are stationary. The Doppler shifts are only due to the displacements of the mobile terminal, but in case of multipath it is not possible to wait in the same place for a while in order to average the results considering that only multipath will be varying, since if nothing moves around the propagation conditions have no reasons to change. Thus, static positioning is much more difficult indoors.

2.3 Main existing approaches

Many positioning systems have been proposed with radio transmitters. All the above mentioned techniques have been implemented and this paragraph proposes a sort of classification depending on the technique. Table 1 gives provides a non-exhaustive summary of them. A few references are provided concerning UWB (Fontana 2004), Bluetooth (Takada et al. 2003), WiFi (Wang et al. 2004) or TV (Martone and Metzler 2005) signals.

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[10] A fourth measurement is required for "synchronization" purposes as long as the receiver is on the earth's surface.

System	Technique			
	Angle measurements	Fingerprinting	Time of flight measurements	Cell-Id
GNSS			✓	
WiFi		✓	✓i	
Bluetooth		✓		
UWB			✓	
GSM/ UMTS	✓ii		✓iii	✓iv
RFID				✓v
TV			✓vi	

Table 1. Summary of a few radio based positioning systems

i.   Since wireless local area networks are not synchronised, distance (and not time) measurements are used. The distance is estimated through a power level measurement and a model of propagation (typically modified Friis formulae where the power of the distance is between 2.5 and 4 depending on the environment). This is not really accurate and too dependent on the fluctuations of the environment.

ii. Angle measurements are already carried out at base stations in order to allow the use of the same frequency channel for transmissions in different directions. Thus, those measurements are available, but the limitations discussed in previous sections still apply.

iii. These networks are not synchronised and mainly differences of time of flight have been proposed (but direct times of flight have also been proposed). Unfortunately, the propagation models are not well suitable and the best reported performance is around one hundred metres outdoors, and can rise to a few hundreds of metres indoors.

iv. Cell-Id is used by networks in order to route communications: once again, this is already implemented in mobile networks because it is needed. The accuracy is typically a few hundreds of metres but it is completely free and available. Many telecom operators propose services based on GSM/ UMTS cell-id positioning.

v.   Many definitions of RFID (Radio Frequency IDentification) are proposed: let us consider this is a short range technology that allows two radio transmitters to exchange data, and identification, for instance. A simple way to carry out positioning (but not the only one) is to consider the cell-id model. The coverage area (or range) of a given transmitter is approximately known: when a second transmitter can connect to it, then it is located in the coverage area. In case of a very short range (say one metre or less), the accuracy of the positioning is thus better than one metre. The consequence is that the positioning is no longer a continuous process in space and time (as for GNSS for example), but becomes typically discrete.

vi. Television signal are available almost everywhere in modern countries: why not use them in order to position a receiver? This idea was developed a few years ago and an accuracy of around ten metres has been reported through time of flight measurement, even indoors.

3. The first GNSS signal approach using pseudolites

Although this chapter is dedicated to infrastructure based GNSS systems, other solutions have been investigated by the GNSS community. For instance, High Sensitivity GNSS, HS-

GNSS, had the objective to provide continuity of service with no additional infrastructure. The simple underlying idea is that the signals are still present indoors, but even lower in the noise than outdoors. Thus, if one is able to design a very highly sensitive receiver, it should be possible to locate indoors. A similar, but not identical, idea led to the design of the so-called Assisted-GNSS (Duffett-Smith and Rowe 2006). The initial goal was also to provide indoor positioning by "aiding" the receiver to find the signals in difficult environments. In such situations, one major problem with stand alone receivers is the impossibility of decoding the navigation message (too long to envisage having good radio conditions for such a long duration). Thus, a solution could be to send the navigation message through telecommunication networks that are widely available indoors. Thus, knowing the message, the receiver is able to use the high-sensitivity in order to acquire the GNSS signals and then is able to calculate a position since all the parameters needed (from the navigation message) are available. High sensitivity and assisted approaches are thus quite complementary.

Unfortunately, with a higher sensitivity, the receiver is now jammed with reflected signals in such a large amount that positioning, although possible, is really bad because there is too much interference. Thus, even if real improvements have been proposed in environments where the signals were just at the detection limit, these approaches are clearly not the ultimate solutions for indoor positioning and continuity of service. One has to move to infrastructure-based techniques.

3.1 Technical historical introduction

In the early 1980s the first ideas of GPS-like signals transmitters arose from the considerations of the obvious limitations of the original system. How to use a GPS receiver when fewer than three or four satellites are available? What kind of approaches could be imagined to position the Mars rover? How to improve the VDOP of the constellation in case a good vertical accuracy is needed? Etc.

One answer could be to increase the number of satellites by a factor of two or three but the associated cost for the relatively reduced increment in performance was judged to be non-viable. One has to find another way. The idea of implementing GPS-like signal generators that could be locally deployed came out: the pseudolites were born.

3.2 The concept of pseudo-satellites

A pseudolite (which comes from the contraction of pseudo and satellites) is a generator that transmits GPS signals but which is not a satellite. Such a generator can easily be deployed on earth in places where the number of visible satellites is too low to allow standard positioning (Klein and Parkinson 1986). The first applications were thus naturally oriented towards open cast mines for optimisation purposes. Indeed, as the mine is dug, the view of the sky is reduced and the optimal number of satellites reduces. Adding a pseudolite allows a continuity of the positioning service to the mine to be provided.

A similar idea was developed in the context of so-called Local Area Augmentation Systems (LAAS) where the problem was to provide a good vertical accuracy to landing planes, for example. We know that this vertical accuracy is linked to the VDOP and that locating a satellite below the plane would greatly improve the VDOP. Since it is not possible, the use of a pseudolite seems once again a good idea (Bartone and Van Graas 2000).

Similar to the open cast mine, the case of modern so-called "urban canyons" are complex environments for GNSS signals (see figure 5). A receiver located between large buildings has some difficulties acquiring a sufficient number of satellites. When having additional signals from judiciously located pseudolites, a normal situation can be obtained, leading to the positioning of the receiver in these kinds of environments.

In the previous three examples, the pseudolite is used in order to "augment" the GPS system, its coverage or its accuracy. But one can push forward the concept towards a completely new system: this was imagined for positioning the Mars rover. A complete set of several pseudolites was deployed on the surface of the planet and the signals used for positioning, the same way it is achieved with GPS signals from space. Based on this idea, it was thought that an indoor positioning system could be designed.
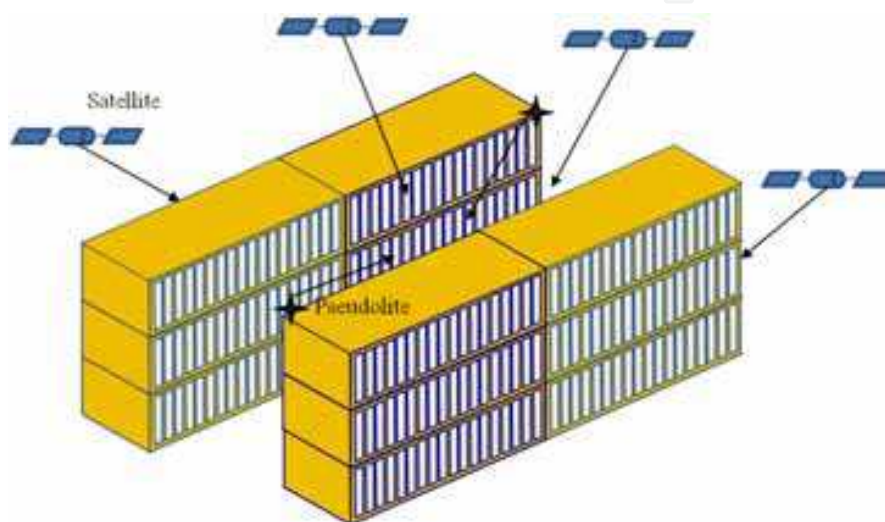
Fig. 5. The urban canyon configuration

3.3 The system for indoor positioning

The basic idea is indeed very simple and is based on the construction of a local terrestrial constellation of GNSS-like signal generators (Kee et al. 2003). They are located at the corners of the building in order to simulate satellites. Figure 6 is a typical distribution although not optimal since the DOP is not very good (please refer to the discussion in previous sections). This is nevertheless a good basis for understanding the concept.

Some major differences apply with comparison to satellites, the most important ones being the immobility of the pseudolites and the shorter distances between the pseudolites and the receiver (leading to unambiguous code for instance, as will be discussed in the next section).

As discussed in previous sections, one has to take care of the initial location considered in the computations of the receiver location since the two possible solutions[11] are not so far

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[11] Remember that four transmitters are used for geometrical (three) and synchronization (one) purposes. The intersection of the surfaces of three spheres gives two points located symmetrically apart from a plane that includes the three transmitters (this comes from the form of the equations that are non-linear). Thus, in case of local transmitters, the final location obtained depends on the initial guess: if it is above the final location it will be the point above the plane, if it is below, the final location will be the point below the plane.

away from each other if one uses the optimal number of transmitters (i.e. four in a 3D positioning system).
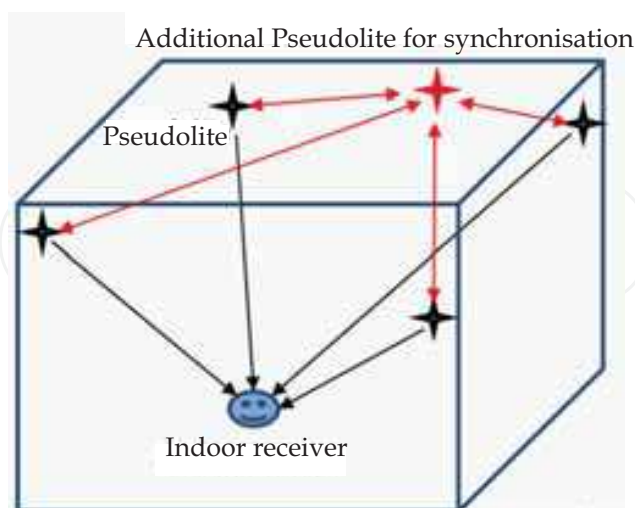

Fig. 6. Pseudolite indoor positioning system

3.4 Advantages and main drawbacks

Such an indoor positioning system is not widely deployed because of numerous major drawbacks, despite some fundamental advantages. Let us list the most important features and comment on whether they are an advantage or a drawback (Kanli 2004).

Continuity with outdoor GNSS: this is obviously a major advantage of the proposed system. Moreover, the continuity is obtained by using the same hardware as for outdoors (since GNSS are clearly a very good candidate when the satellites are visible and is almost free[12]). Note that using GNSS-like signals means that current receivers are already capable, with a software update, of processing them. This fact constitutes a second major advantage. The first drawback is the need for a local infrastructure.

Synchronisation between pseudolites is required. Satellites include atomic clocks or masers in order to reduce significantly the time drift but require a terrestrial infrastructure for synchronisation purposes. In the case of pseudolites, two approaches have been proposed: synchronous and asynchronous systems. In the latter case, the pseudolites are not synchronised and the measurement technique must carry out a sort of synchronisation: the method used is the double differencing that allows us to get rid of the synchronisation of the transmitters. The major drawback is then the need for a reference receiver that should be in radio visibility of the transmitters. Apart from the deployment complexity that this adds, a data link has to exist between the two receivers. This first approach is not intended to be selected for indoor positioning purposes. The other approach uses synchronous pseudolites. Several methods have been proposed: the simplest one in theory, but not in practice, is to link the various transmitters by wire. In such a case a sort of calibration phase is required in order to know precisely the delay between pseudolites. An implementation of this approach used a master receiver located in a known location with respect to all the pseudolites.

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[12] A GNSS receiver integrated into a modern device is estimated to cost a few dollars.

Calculations are then carried out at the master receiver and synchronisation values are sent back, through wires, to the pseudolites. Another way consists in transmitting these synchronisation data through a wireless link, leading this time to latency problems and potential interference (but this is an interesting approach). In addition to this concept, one imagined working the other way round by placing the receiver (which listens to the signals) in the same place as the pseudolites. By considering that one (or several) pseudolites are "pilot(s)", the receiver can synchronise its own pseudolite if it knows the distance(s) that separate(s) it from the pilot(s) pseudolite(s). The difference between received times for two different pseudolites (indeed the associated receivers) allows the synchronisation of the pseudolites. This once again requires data links. Of course, these solutions are clearly adding cost and complexity to the system.

Another simple approach consisted in locating pseudolites in places where the GNSS signals are available, namely outdoors, and to use the constellation time to synchronise the transmitters.

Code and carrier phase measurements are possible. In the first case, code phase measurements are carried out: the positioning accuracy of the pseudolites needs to be in the range of a few decimetres. The resulting positioning is intended to reach a few meters, as outdoors. Note that multipath are bound to largely degrade this very optimistic goal (discussion follows). The other approach described is based on carrier phase measurements (Kee et al. 2001, Rizos et al. 2003). We know that this kind of measurement is much more accurate but suffers from the ambiguity resolution problem. Nevertheless performances reported are in the range of a few centimetres[13]: the requirement in terms of pseudolite location accuracy is also increased to typically one centimetre (this task is not so easy to carry out).

Ambiguity is no longer such a difficult problem. In the case of code phase measurements, ambiguity is totally suppressed since indoor distances are much smaller than three hundred kilometres. In the case of carrier phase, ambiguity is still present but is not so high: typically fifty metres for indoor distances, the carrier phase ambiguity for frequency L1 is around 260. Current works are evaluating the possibility to use classical code phase ambiguity resolution methods for the carrier phase resolution indoors.

A *potential accuracy of a few centimetres* is achievable with the carrier phase approach, even if these measurements are probably not the most important ones for the foreseen applications looking forward to the continuity of the positioning for mobile phones. Nevertheless this is significant of the capabilities of the principles.

Near-Far effect is a new propagation concern (Madhani et al. 2003). Since the deployment complexity of the pseudolites must be reduced, their number should be reduced to a minimum. As a corollary, the distance between pseudolites should be increased to a maximum. Unfortunately, the Pseudo Random Noise (PRN) codes used in the case of GPS, for instance, have auto correlation functions that present some secondary peaks. These secondary peaks can have amplitudes of about -24 decibels (dB) in comparison to the main peak. This is very good for outdoors where the difference of distances from various satellites

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[13] Techniques similar to high accuracy methods for outdoors are used together with the associated problems such as the determination of the initial location.

can reach a maximum of less than 2dB, but is a real problem indoors. In terms of phenomenon, the problem is related to the fact that if secondary peaks of a transmitter are greater than the main peak of another, then this second one will appear as noise and will not be detectable. This 24dB margin in power is reached as soon as the ratio between the closer and the farther transmitters reaches four: this is not an unusual situation indoors. Thus, a few solutions have been proposed, among which: 1/ pulsed transmissions consisting in allocating between 10 and 20 percent of the time to a particular pseudolite (this has shown to provide an additional margin of about 10dB corresponding to nearly an additional factor of two in distance), 2/ frequency shifts in order to almost eliminate the near-far effect, but at the cost of a substantial increase in the terminal complexity or 3/ in sophisticated mitigation algorithms that successively suppress the more powerful signals to finally extract the lowest one.

Interferences with outdoor signals. Another advantage of pseudolites is the ability to decide the power level to be transmitted, depending on the required coverage and performance, and of course on the environments. This advantage becomes a major drawback when thinking in terms of cohabitation with the outdoor world (Glennon et al. 2007, Yang and Morton 2009). If one takes the case of GPS (but this is true whatever the system considered), using GPS-like signals for indoor transmission is susceptible to create interference with the signals that could be received by an outdoor receiver receiving signals from the satellites. As a matter of fact, the same phenomenon as described indoors for the near-far may occur. Thanks to GPS project management, some specific PRN codes have been reserved for pseudolite operation[14] at the early stages and this interference problem is slightly relaxed, but is still a real concern for GPS authorities. A specific section, at the end of this chapter, is dedicated to the regulations restricting the power levels allowed to be transmitted for indoor operations.

Finally, *multipath* are a major issue. Mitigation techniques must be found in order to imagine a proper operation of the code phase pseudolite system. This topic is such a challenge that the next section is dedicated to it.

3.5 The specific problem of multipath in indoor environments

As already discussed in previous sections, indoor environments are characterized by the presence of many reflectors in the path from the transmitter and the receiver. All these reflected signals are going to combine at the receiver end and produce the really received signal on the receiver antenna. This signal is the one that the receiver is going to deal with since this is the real physical received signal. As this is not only the direct signal from the transmitter, and depending on the signal processing techniques used, the distance finally measured can be erroneous (remember that as a matter of fact, this is a time that is measured and not a distance).

From a physical point of view, the situation can be seen as follows: the physical quantity that is transmitted is indeed an electric field, given in V/m. It is furthermore characterized by a frequency, an amplitude, a phase and a delay, in comparison, say, with the first

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[14] PRN 1 to 32 are reserved for so-called space vehicles, the satellites, and PRN 33, 34, 35, 36 and 37 are reserved for terrestrial transmitters.

arriving signal. Let us consider that the frequencies of all the reflected signals are identical[15]. Then, the physical phenomenon that occurs is simply an addition, in amplitude, phase and delay, between all the reflected signals (and the first one, which should be the direct path[16]). The problem is now to be able to get rid of all contributions except the first one (which should be the direct path under our assumption). Such a time discrimination is somehow equivalent to the synchronisation problem and requires theoretically a radio bandwidth proportional to the time discrimination interval wanted: in our case, where nanoseconds are sought, this bandwidth is too large and other approaches must be found.

Let us now come back to the specific problem of multipath in GNSS, and to GPS for illustration. The way time separation is obtained, from the transmitter to the receiver, is based on the famous auto correlation function (ACF) of the codes. A typical such function is given in figure 7.

In case of multipath, we are interested by the main lobe of the ACF. Let us consider only one reflected path (in addition to the direct path) for simplicity of explanations, knowing that this is clearly not a real situation. If the reflected path is delayed by more than one and an half chip, the ACF of the incident signal (which is composed of the direct and reflected paths) with the receiver generated replica has the shape given in figure 8. Remember that a GPS chip length is given by 1/ 1023 milliseconds, hence 977.5 nanoseconds, which in turn corresponds to 293 meters. Thus, figure 8 is characteristic of a reflected path delayed by more than 440 meters. The receiver will be able without any problem to find the direct path considering (this is the assumption that is classically made) that the first peak of the ACF is the value being sought.
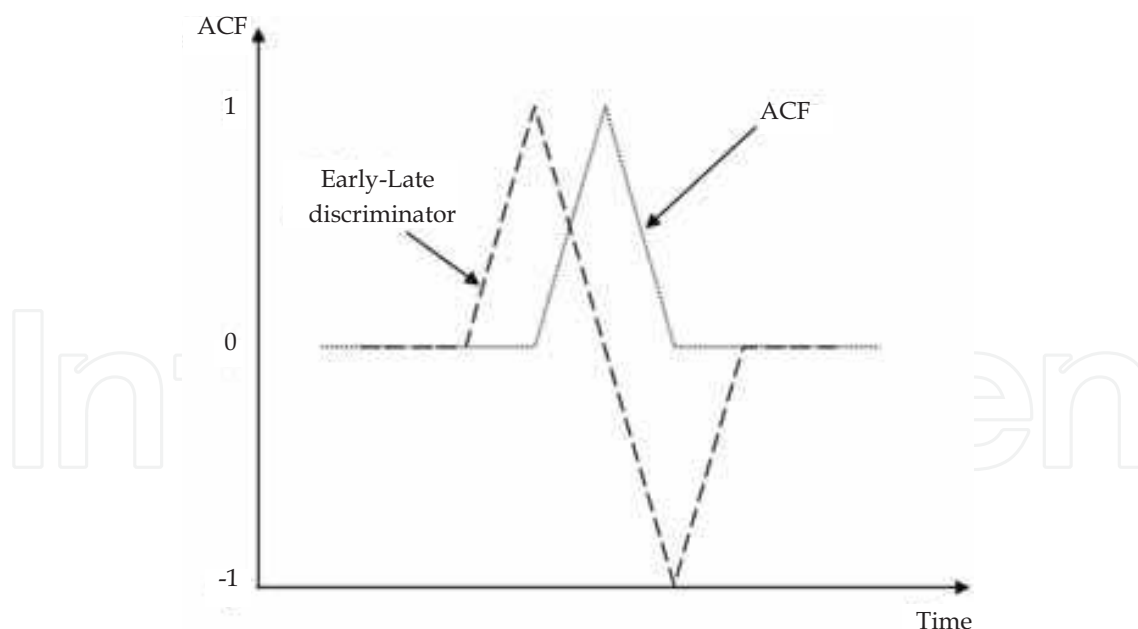
Fig. 7. Typical autocorrelation function of a GPS code

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[15] This could not be true in case of reflection on moving objects, such as cars for example. But in our indoor case, we are going to consider this hypothesis as correct.
[16] The direct path could not be present and then the first received signal would also be a reflected path. This situation is one that we are not going to deal with in this chapter.
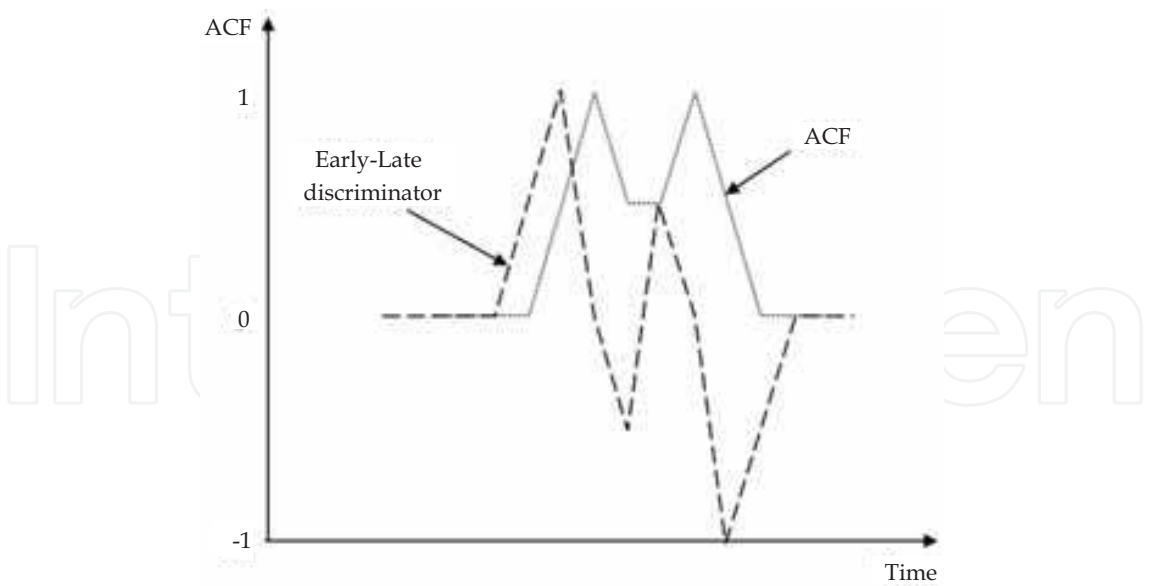
Fig. 8. Typical autocorrelation function for a large delayed multipath
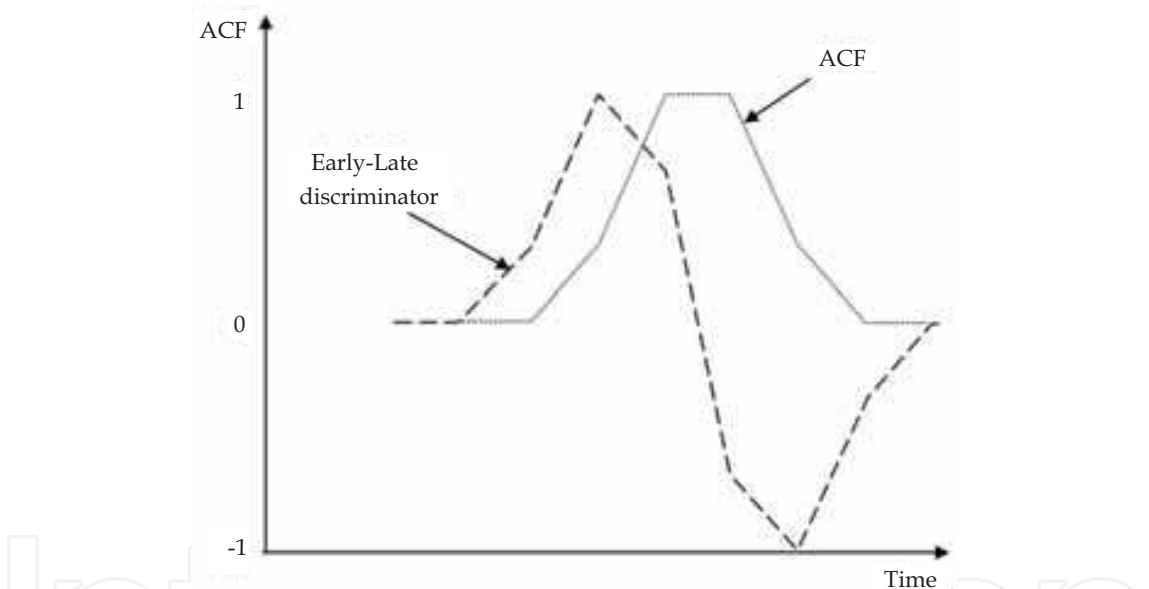
Fig. 9. Typical autocorrelation function for a small delayed multipath

Indoors, reflected path have delays that are indeed much smaller. In such a case, the ACF is completely disturbed (see figure 9) and can take many different shapes. The problem is now that the receiver will be fooled when detecting the maximum of the ACF which is no longer at the time of arrival of the direct path. Note also that this maximum now depends on the relative phases, delays and amplitudes of the direct and reflected paths.

The classical way this multipath effect is characterised is given in figure 10. This curve allows the comparison of various multipath mitigation techniques, as illustrated in figure 10 for the Standard Digital Locked Loop (SDLL) and the so-called Narrow Correlator (NC). Note the reading of the figure: considering a direct path and a single reflected path of amplitude half that of the direct path (only suitable for comparison purposes and certainly not for

evaluation purposes, since this situation is clearly not representative of reality), the envelope of the resulting error in pseudo-range measurement is drawn. The upper curve corresponds to reflected path in phase with the direct signal, when the lower curve is related to the case where the reflected path is out of phase with the direct path. Note that SDLL is absolutely not suitable for indoor environments since errors as high as 60 meters are possible[17]. The same almost applies to the Narrow Correlator[18] since errors of 10 metres are still possible: if the goal of accuracy is in the range of a few metres, this approach is also not viable.
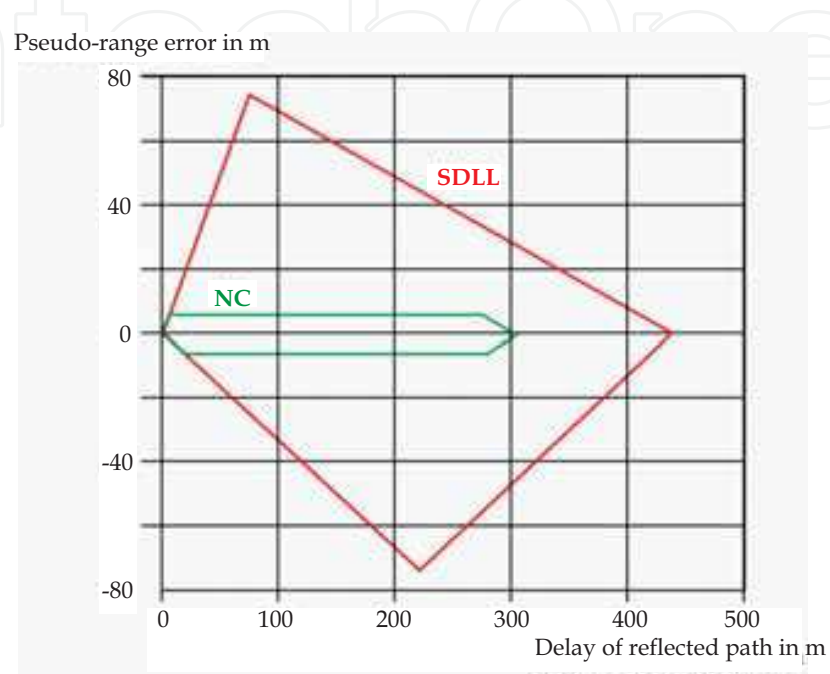
Fig. 10. Multipath effect of the pseudo-range measurement
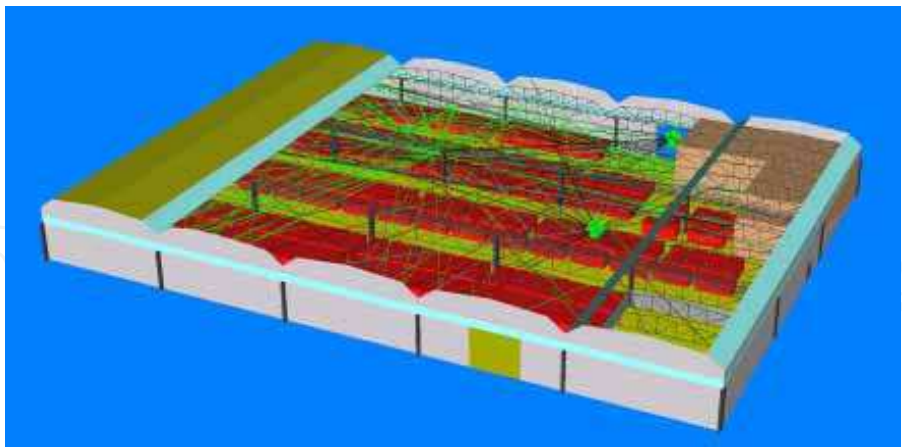
Fig. 11. Typical multipath environment indoors

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[17] Here one has the explanation why no commercial solutions are available in the field of code phase pseudolites!

[18] Another constraint of the Narrow Correlator is the need for a receiving bandwidth of at least 8 MHz, which is not the current standard. Nevertheless, the standard is bound to evolve with the advent of Galileo in the frequency band L1/ E1 since the current 2 MHz are too narrow for an acceptable detection of their signals.

Let us now come back to real situations where several (many indeed) multipath are present. In order to give an idea of such configurations, we consider the environment described in figure 11 which is a large car park. The structure is made of metallic beams and concrete walls. Cars are also modelled as red parallelepipeds. In figure 11 are also shown the path from transmitters to a receiver that is located in the centre of the building. The black paths are direct ones, while the green ones are reflected path: the conclusion is quite clear! In such cases, one can easily imagine that the ACF is even more disturbed than the ones proposed in figures 8 and 9.

3.6 The performances attainable

The preceding pages have shown that the only multipath problem is enough to disqualify the pseudolite approach which uses code phase measurements. A few other multipath mitigation techniques are potentially available, such as the Strobe Correlator or the Double Delta correlator, but both require rather a high signal to noise ratio (SNR) in order to properly function[19]. This is not so easy to obtain indoors since reflected paths are bound to reduce significantly the signal to noise ratio (by destructively combining the electric fields). Thus, this kind of systems is not yet available with acceptable performance.

The other possibility is to use carrier phase measurements that we know are less sensitive to multipath (because the ambiguity is reduced to nineteen centimetres instead of three hundred metres for code phase). Unfortunately, carrier phase based systems are more complex to use in practice because they require both an initial location which is accurate to a few decimetres and the carrier phase to be followed continuously, which is much more difficult than to follow code phase. Such systems exist but are not widely deployed for these additional reasons (in conjunction with the need for infrastructure).

3.7 Short synthesis

Pseudolite systems require an infrastructure deployment and synchronisation, and have to cope with near-far and multipath but provide full continuity with the technical approach for outdoors, GNSS, with only minor modifications to the receiver. This is a good candidate if no solution without infrastructure can be found but the community of service and application providers is not yet ready to accept such a solution, except in situations where an installation cost is counterbalanced by already well identified revenues.

4. The first step in overcoming some pseudolite linked problems: The repeaters

Following pseudolites, one tries to propose ameliorations to the main drawbacks (Im et al. 2006, Jee et al. 2004). Since it is based on transmitters, the infrastructure is still present, but some approaches reduce its complexity by the introduction of the concept of a "common signal" to all the transmitters (Caratori et al. 2002).

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[19] The Narrow Correlator is the only one that does not degrade the SNR while improving the multipath behaviour.

4.1 Introduction to the basic idea

The first simplification concerns the synchronisation. In a similar way that outdoor pseudolites can synchronise themselves using GNSS signals, the idea here is to put an outdoor antenna on the roof of the building in order to obtain the constellation signals. Note, that in this case the antenna is probably (certainly indeed) receiving several satellite signals. Here is taken into account the second new idea that consists in forwarding this signal to the transmitters: the innovation lies in the fact that the same signal (which is probably made up of many satellite signals, as mentioned) will then be transmitted from the various transmitters, now called repeaters[20]. In this way, an obvious problem appears: if the repeaters are transmitting simultaneously, the same signals will be transmitted from different locations and, once received by the terminal, will certainly be considered as reflected paths. Since the principle is to carry out time measurements, and thus distance measurements, it is clearly not acceptable. Thus, the transmission is now achieved in a sequential manner with always only one repeater transmitting at a given time. This presents another interesting advantage: the near-far effect is now removed[21].

4.2 The systems proposed

Two measurement systems are then possible.

- The first one carries out the computation of the location, at the receiver's end, for each transmitter successively. At each corresponding time the fourth coordinate (the so-called clock bias[22]) of the navigation solution vector is recorded. As soon as four successive computations have been obtained, it is possible to compute the indoor distances through the calculations of the differences between the fourth coordinates considered at different time. These differences give a new system of three independent equations that can be solved classically. The resolution gives the indoor location of the receiver. A short demonstration of this principle is given below.
- The second one carries out some differences of pseudo-range measurements at the precise instant of the transitions from one repeater to the next (Fluerasu et al. 2009, Fluearsu and Samama 2009). At these instants, the difference of the pseudo-ranges that are measured just before and just after the transition shows the value of the difference of distances between the two repeaters and the receiver. In order to obtain the indoor distances, a second difference is needed, as briefly explained below. Note that this approach also removes all the effects whose second derivative is zero, including

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[20] Please note that if the term is appropriate since transmitters are just "repeating" the outdoor received signal, it should not be confused with the classical repeater that is used for demonstration purposes or just for having outdoor signals available indoors. Here repeaters represent a new approach for indoor positioning and should be seen more as a means of improving some aspects of pseudolite rather than just forwarding signals. It is so true that all the sections could have been written with a signal generator instead of the outdoor antenna.

[21] Only the dynamic range is now a limitation when the receiver is processing signals from two successive repeaters.

[22] This is clearly not the clock bias, but indeed the sum of all contributions that are common to all the satellites that are considered for the resolution: thus, this included the free space indoor distance that we want to obtain.

atmosphere propagation or the major part of clock drifts. This new differential mode is also susceptible to increasing the positioning accuracy.

Let us deal briefly with the mathematics of the first approach based on clock bias analysis. The method is based on the use of the clock bias coordinates. As described above, once one has carried out four receiver location computation (one for each repeater), a new vector is available, where the ct_i are the calculated fourth coordinates, the $ct_r(i)$ are the real clock bias of the receiver at each transmission times and the d_i the distances separating the repeaters from the receiver.

$$\begin{bmatrix} ct_1 \\ ct_2 \\ ct_3 \\ ct_4 \end{bmatrix} = \begin{bmatrix} ct_r(t_1) + d_1 \\ ct_r(t_2) + d_2 \\ ct_r(t_3) + d_3 \\ ct_r(t_4) + d_4 \end{bmatrix} \qquad (1)$$

The unknown variables are now the d_i, but the problem appears to be the real clock bias of the receiver which is naturally not a constant. Thus, in (1), one has not only the four d_i unknowns, but also the four clock biases. The technique consists indeed in estimating the clock bias difference between instant t_2 and instant t_1 by the way of the clock drift computation carried out through Doppler measurements by the receiver. Thus, the idea is to consider that:

$$ct_r(t_j) = ct_r(t_i) + \sum_{k=i+1}^{j} cdt_k \qquad (2)$$

Where cdt_k is the clock bias rate (called the clock drift) at time t_k. The various $ct_r(t_i)$ of (1) are now reduced to a single unknown, $ct_r(t_1)$. In addition, one knows that the four distances d_i are characterised by only three spatial coordinates, x, y and z of the receiver once the coordinates of the repeaters are known: this is a system requirement to provide the receiver with these coordinates. The indoor location computation is then carried out typically through hyperboloid intersection, as soon as the receiver is able to determine which repeater is transmitting at any given time. This is achieved through synchronisation which is made possible since the signals transmitted by all the repeaters are identical (thus, there is just the need for an initial calibration of the wire delays between the signal generator, or the outdoor antenna, and the repeaters).

On the other hand, the need to estimate the clock drift is somehow a constraint since the final performances will greatly depend on the quality of the receiver clock. Thus, another approach was proposed, based simply on classical measurements carried out by all current receivers: the raw pseudo-ranges. When one draws the difference of pseudo-ranges from one instant to the next in a repeater like system, the curve of figure 12 is obtained (note that in this example only three repeaters are deployed, leading to a 2D positioning).

Clear skips, called "transitions" in the figure, can be seen: they correspond to the difference of distances, d_j-d_i, that characterises the increase or decrease of the distance from repeaters to the receiver when the transmitted signal switches from repeater i to repeater j. It is positive when the distance increases, and negative otherwise. Note also that two additional phenomena are present: 1/ a slow constant increase in the equilibrium value (which

represents the remaining contributions whose first derivatives are not zero, for example the clock acceleration) and 2/ a characteristic shape of the curve just after the skips, which is due to the receiver's loop that tends to come back to the equilibrium after this destabilisation. Note that the sum of the transitions, for a complete cycle should be zero. Of course, due to measurement errors, this is usually not the case, and the choice of the best transitions to be considered for positioning has to be carried out.
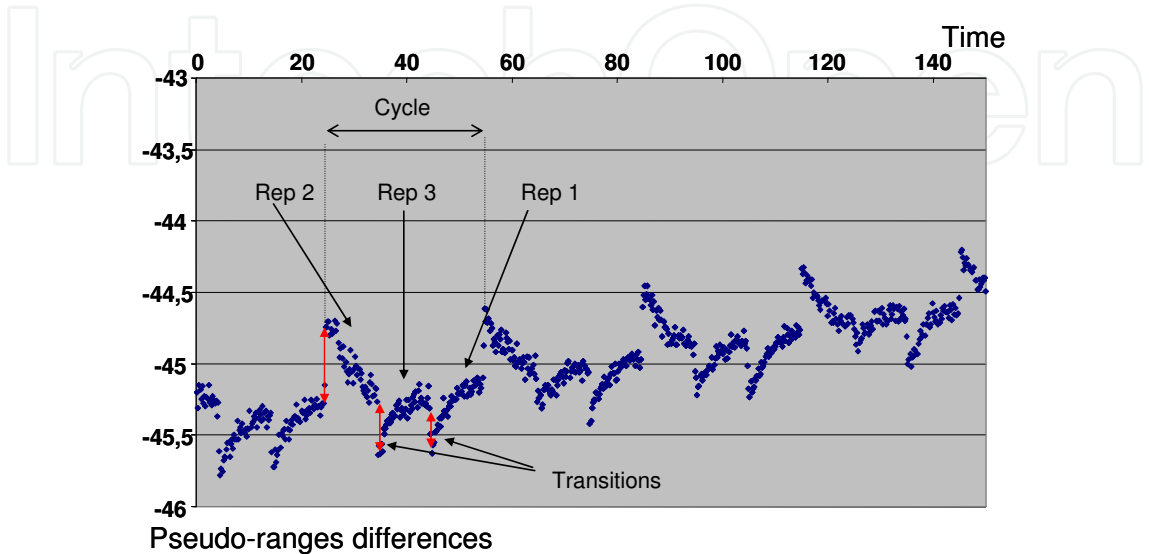
Fig. 12. Typical response of a receiver

The curve of figure 12 is a single difference of raw measurements. In order to extract the differences of distances mentioned above, there is the need to carry out, at the precise instant of transition, a second difference between two successive single differences. Thus, a process of double differencing is the basis of this proposed approach to repeater positioning. Following these measurement steps, the computations are similar to those described for the clock bias based approach.

4.3 The performance achieved

The most often implemented approach is the second one because it is simply based on classical measurements of GNSS receivers and that no additional computation errors affect the positioning. Tests have been carried out in various environments: each time, the system was deployed and positioning carried out with different receivers. Note that the receivers used are so-called software defined radio (SDR) receivers since the method is affected by multipath, in a similar way that pseudolite based systems are. Thus, a specific mitigation technique was implemented (described in a following section) which required the tracking loops to be slightly modified. Since proprietary receivers do not allow such modifications, an SDR receiver was required. It should be pointed out that transmitters are located in such a way that walls are included in the propagation path from the transmitters to the receiver. These environments, together with their "Ergospace[23]" representations, are as given in figures 13 to 16 below.

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[23] Ergospace is the electromagnetic propagation software used for the deployment phase. The main goal is to evaluate the multipath related effects.
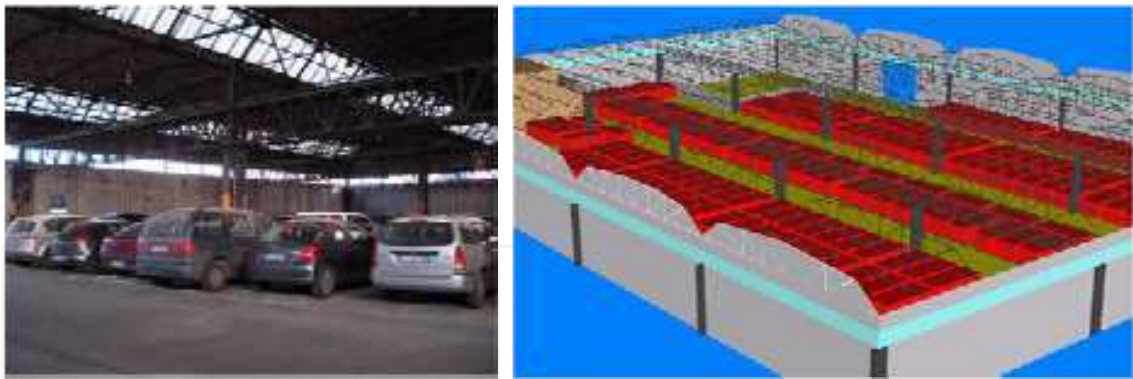
Fig. 13. A car park

Fig. 14. An entrance hall

Fig. 15. Classrooms

Fig. 16. An amphitheatre

The system used for these experiments consists of a few (typically four) transmitters which are located indoors and which transmit a signal provided by a GNSS-like signal generator (we used both an AeroFlex GPS-101 and a Spirent GSS6560). Note that only one such signal is required since the approach proposed is based on the transmission of the same signal through the various transmitters deployed. Note also that in order to satisfy the ongoing various regulations (both in the US and in Europe, briefly described in a following section) the power transmitted is limited (from -80dBm to -65dBm). The principle of the approach is given in the figure 17. The transmitting antennas had a radiating pattern with a maximal gain of around 3dBi.
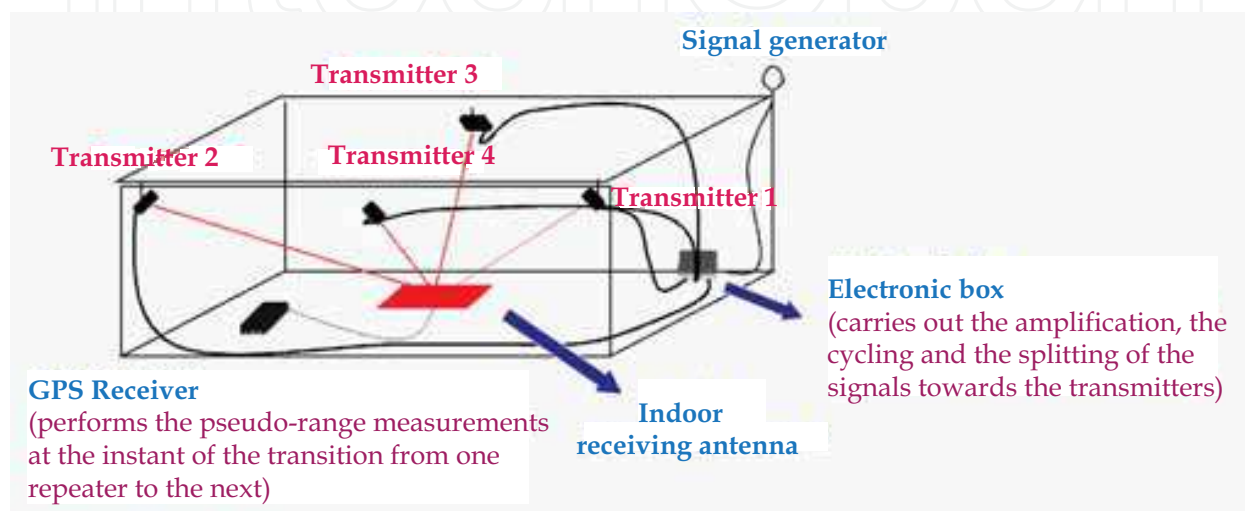
Fig. 17. The system as it was deployed

A summary of the results obtained, all environments included, is given in figures 18 and 19. The first figure shows the results obtained in classrooms, an amphitheatre and an entrance hall. About 20 different locations have been tested in these environments. The various curves represent different ways to filter the resulting fixes obtained. The "unfiltered" curve takes into account all the fixes, with no filtering at all. The other three curves, named "-xm", give the resulting fixes obtained once we remove the ones that are outside the largest rectangle defined by the locations of the transmitters by more than x metres. Note that this is achieved for two main reasons: outside this rectangle, the DOP values increase very rapidly and the positioning algorithms sometimes do not converge.

Figure 19 is a summary of the results obtained in all experiments and with various receivers. In red in the figure are the results obtained in the car park, and the two blue curves are the results obtained in the other environments described. The two curves have been obtained with -80dBm and -65dBm respectively.

The main conclusion is that the current performances are roughly in the range of 3 to 4 metres for 80% of the fixes. It is of uppermost importance to understand that this can be considered as really raw fixes since calculations are carried out totally independently from one fix to the next. It is highly probable that basic smoothing or filtering (applied on pseudoranges or locations) would lead to a significant improvement. In addition, a complete continuity with outdoor GNSS is achieved since velocity computations are also possible (Samama and Vervisch-Picois 2005).

Real Accuracy - % of total fixes
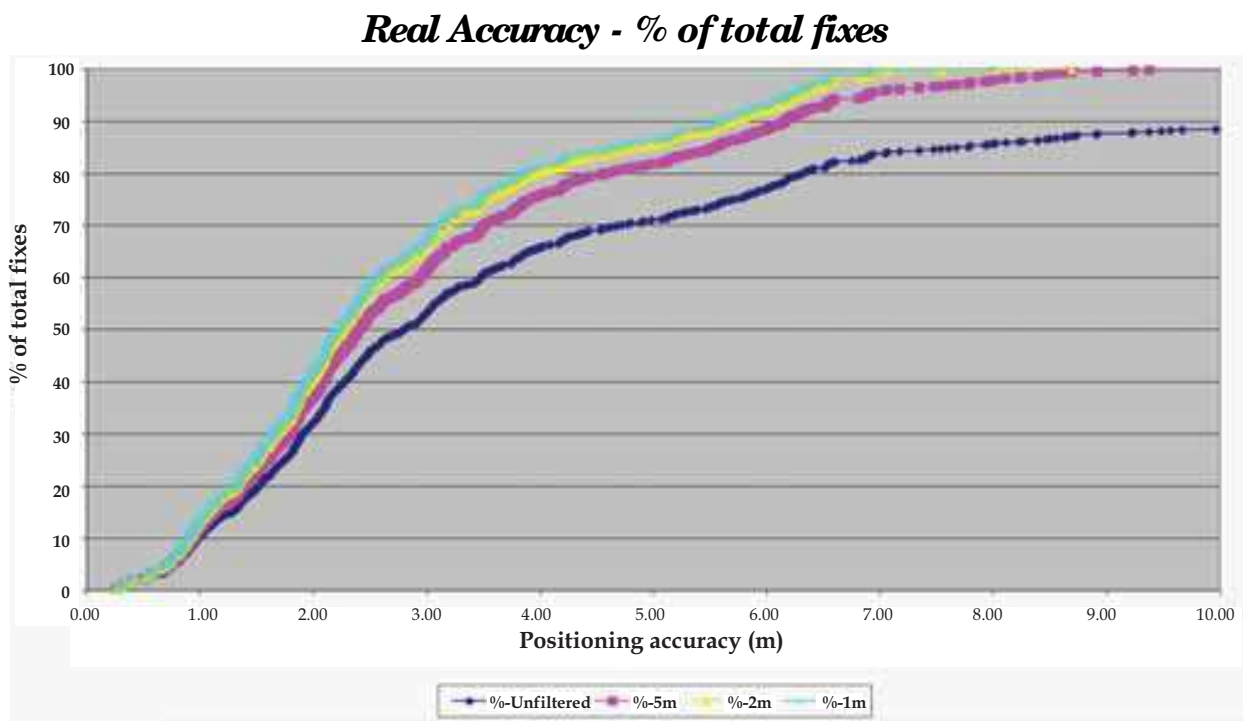
Fig. 18. Results obtained in classrooms, amphitheatre and hall

Real Accuracy - % of total fixes
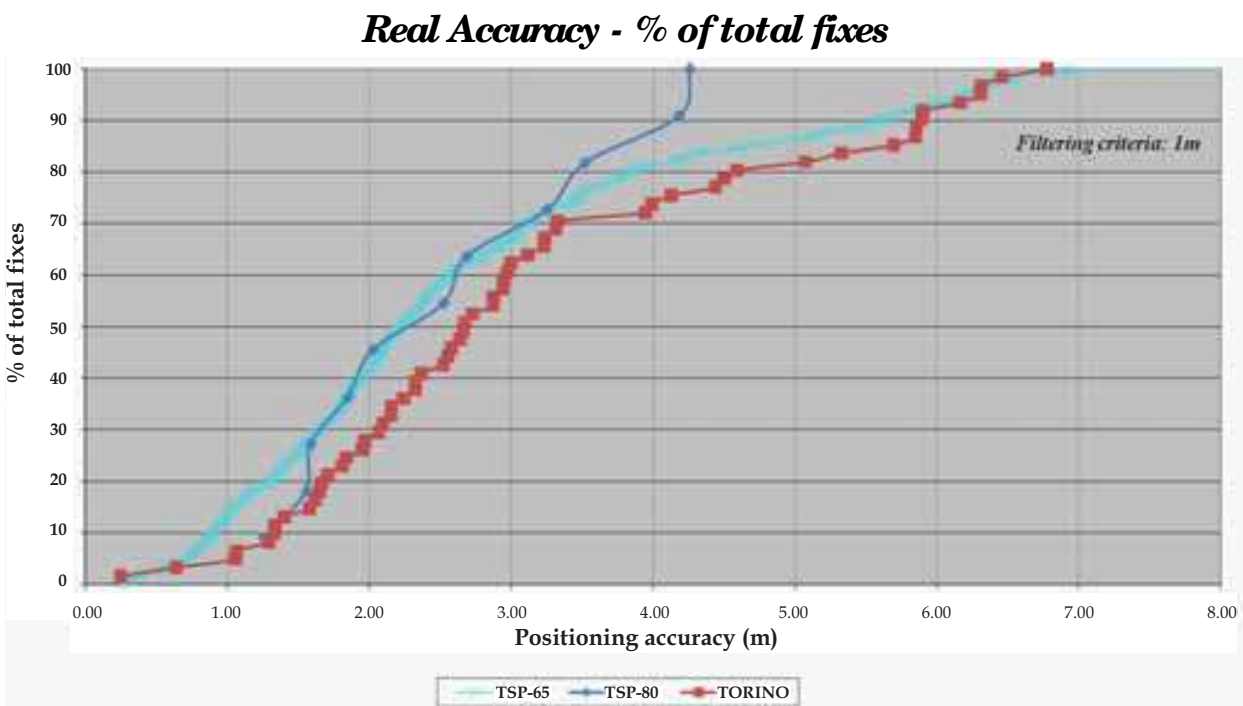
Fig. 19. Summary of all the results

4.4 The main limitations

Synchronisation, absence of near-far effect and implementation of a differential approach are the main competitive advantages of repeaters over pseudolites. Unfortunately, they go with a few disadvantages, described below.

- Carrier phase measurements are no longer possible (or in reality certainly very complex to carry out) since the skips that are the basis of the method, mean that the phases are lost at each transition, leading to the need for a new search for the integer ambiguity number at each transition. Thus a few meters of accuracy is the goal of this system: enough for the continuity of service, but improvement directions will not be easy to find.

- The sequential scheme is a problem when one wants to address dynamic positioning since the time the cycle takes should be taken into account in the displacement. This is quite complex to implement and only slow movements can be dealt with. This is acceptable for pedestrians in a commercial mall, but not for a car in a tunnel. This sequential technique is very interesting for time based double differencing, but not for dynamics where additional errors are present.

In addition, the multipath problem (Kaplan 2006) is not solved by the repeater concept and since code phase measurements are typically carried out, it has to be solved: this is the topic dealt with in the next section.

4.5 The multipath mitigation technique developed

This paragraph addresses a "short multipath insensitive code loop" (SMICL) mitigation technique, developed in the context of the repeater based positioning system: the goal is to mitigate multipath (Jardak and Samama 2010). For this, a new discriminator function has been proposed which is insensitive to multipath signals having relative delays of less than 146.5 m, equivalent to half a chip length. The standard discriminator used by the Standard DLL (SDLL, the DLL having a correlator spacing of 1 chip), has a non zero steady state error in the presence of multipath signals. This is due to the non-symmetrical behaviour of the composite ACF. As a result, when the early autocorrelation value equals the late autocorrelation value, the prompt replica is not synchronized with the direct signal, but rather with the composite signal. Consequently, another discriminator function was found: the proposed code discriminator compares the early correlation value to an adjusted version of the prompt one. The result is that the new discriminator expression yields zero when the prompt reaches the delay of the direct signal component even in presence of multipath rays of relative delays less than half a chip.

The proposed new expression of the discriminator is given by:

$$D = \left(IE^2 + QE^2 \right) - \left(IP'^2 + QP'^2 \right) \tag{3}$$

Where

$$\begin{cases} IP' = IP - \dfrac{\Delta}{2} \dfrac{IE + IL}{2 - \Delta} \\ QP' = QP - \dfrac{\Delta}{2} \dfrac{QE + QL}{2 - \Delta} \end{cases} \tag{4}$$

Δ is the correlator spacing and IE, QE, IL, QL, IP and QP are respectively the in phase and in-quadrature phase of the Early, Late and Prompt classic correlators. Note that modified prompt correlators are introduced, IP' and QP', as described. Expression (3) is based on the

fact that the left part of the ACF is the one that is the least modified by multipath, but that in addition the prompt replica is modified by the presence of multipath. Thus, the new discriminator uses the Early correlator that is less modified and a modified form of the prompt correlator. Expressions (4) represent the way the prompt correlator is modified and are in fact obtained from the analysis of the general form of the multipath contribution to the discriminator. Indeed, for multipath of less than half a chip, one can show that

$$\begin{cases} IE + IL = (2 - \Delta) \sum_{0 \le k \le N} A_k \cos\left(\theta_k - \hat{\theta}\right) \\ QE + QL = (2 - \Delta) \sum_{0 \le k \le N} A_k \sin\left(\theta_k - \hat{\theta}\right) \end{cases} \tag{5}$$

The various sums in (5) being the multipath contributions, considering there are N reflected paths of amplitudes A_k and delay $(\theta_k - \theta)$. The limitation of the efficiency of the method to reflected paths of less than half a chip is due to the validity domain of these approximations.

Let us now give the main results obtained for multipath mitigation. The proposed code loop is compared to the standard code loop and the Narrow Correlator (NC). The signal received is assumed to be the sum of a direct signal and a single reflected signal whose amplitude is half that of the direct signal. The following curves show the envelopes of the pseudo-range errors in a similar way as in figure 10.

With an unlimited front-end bandwidth receiver, the results are given in figure 20. The half chip limit is quite clear for the SMICL. Nevertheless, performances are better than SDLL and NC for short multipath[24].
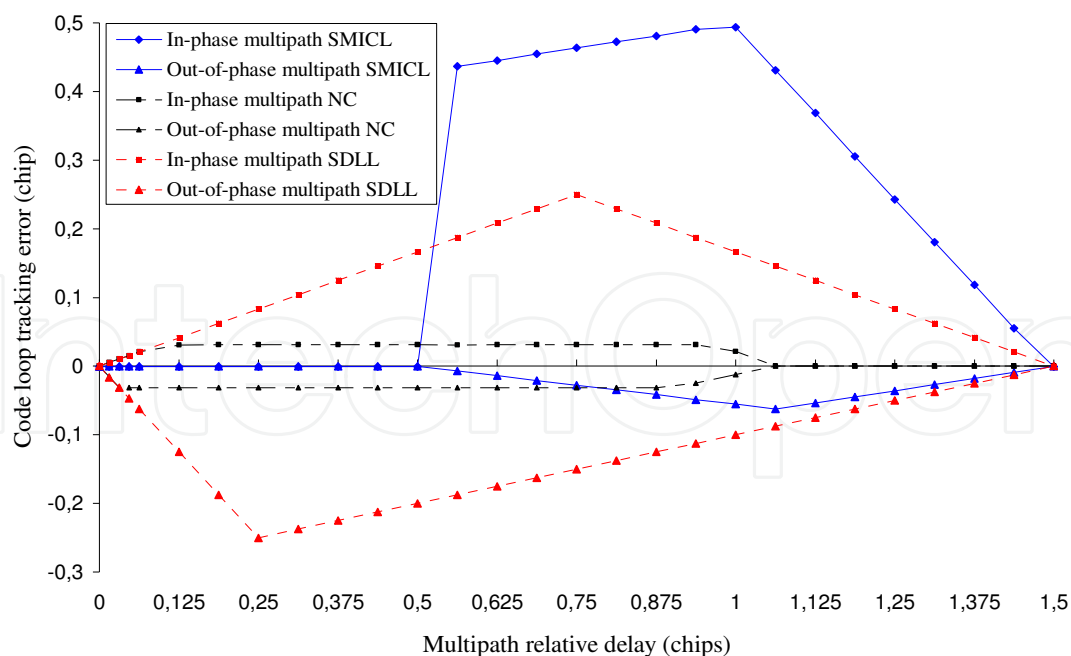
Fig. 20. Comparison of discriminators for an unlimited bandwidth

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[24] Many simulations, carried out with Ergospace, have shown that this assumption concerning the delays of the reflected paths indoors is acceptable almost all the time.

With a 2 MHz front-end bandwidth receiver, the current standard for GPS receivers, things are a little bit different[25]. The performances are in this case reduced (the efficiency is not as good for mitigation), and a typical result is an equivalence between the SMICL (at 2 MHz) and the NC (at 8 MHz). Thus, the SMICL allows one to obtain performances of the NC with the current available bandwidth. This is a nice result but it is not sufficient since we showed that 10 to 12 metres of accuracy is not enough indoors. Thus, a 2 MHz bandwidth is not sufficient.

With an 8 MHz front-end bandwidth receiver, which is an intermediate plausible value for future GNSS receivers (including Galileo), the ACF is very close to that obtained with the theoretical unlimited bandwidth. The performance of the SMICL is then acceptable, as shown in figure 21 which compares NC and SMICL. Note that the vertical axis is now given in "chip" (0.01 is equivalent to approximately 3 metres). Based on this figure, multipath errors are reduced with the SMICL to three meters in the worst case (very short out-of-phase multipath) and to 0.7 m when the relative delay is between 0.1 and 0.5 chip.

Please keep in mind the fact that these results are obtained with only one reflected path. Some other simulations were carried out in the case of a typical environment involving several multipath rays and showed that the code measurement error due to multipath is also significantly reduced when the SMICL is considered.
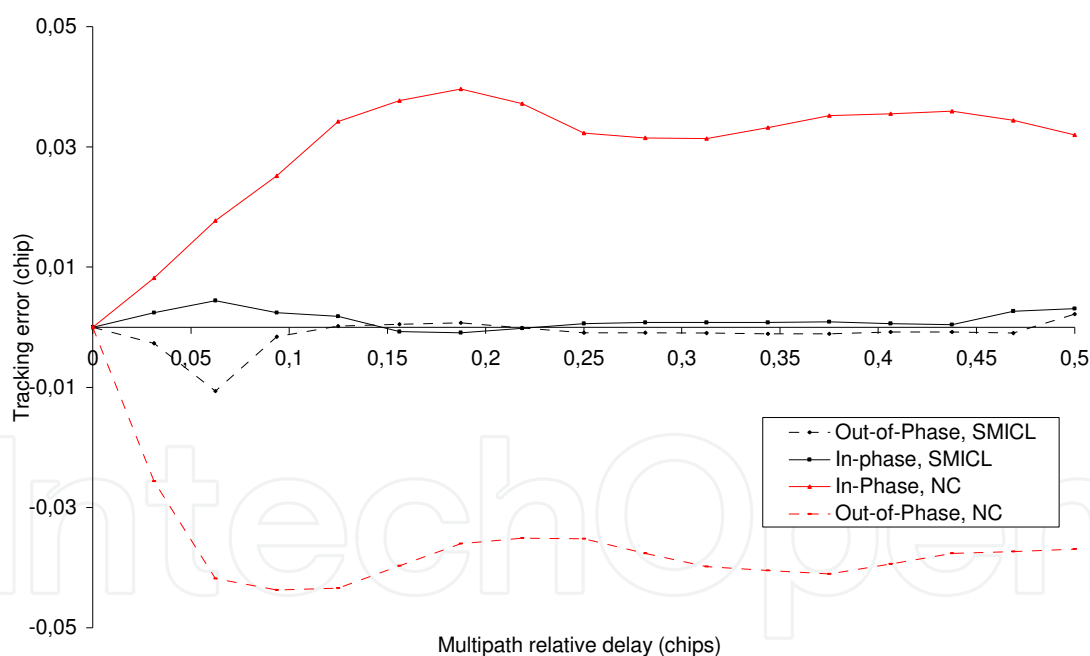
Fig. 21. Comparison of SMICL and NC for an 8 MHz bandwidth

4.6 Discussion

If one combines all the advantages of both pseudolites and repeaters, only the need for a local infrastructure and the multipath effects are not dealt with. The repeater based

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[25] Once again, there is a direct link between multipath mitigation efficiency and bandwidth.

infrastructure is still required, although using only one signal distributed to all the transmitters clearly constitutes a huge improvement (also in terms of synchronisation). On another hand, multipath mitigation with the SMICL has shown impressive results that have been validated experimentally, as can be seen through the experimental results. But even with the SMICL, the repeater approach has two major limitations: the difficulty to carry out carrier phase measurement, hence limiting the accuracy attainable (although this is sufficient for the continuity with GNSS outdoors), and poorer performance in dynamic modes. The goal of the next step presented is to propose a synthesised approach that could be the way to overcome these last limitations.

5. The repealite concept: Mixing the advantages of both pseudolites and repeaters

The cycling approach, implemented until now, has a great disadvantage: carrier phase measurements are almost impossible. In order to improve the indoor accuracy, a new approach is proposed based on the so-called "repealites[26]" approach which tries to cumulate the advantages of both repeaters and pseudolites (i.e. carrier phase measurements and same signal transmitted through all the transmitters). First theoretical works have shown a potential of less than one metre accuracy by implementing classical code measurement smoothing techniques using carrier phase measurements. The remaining problem is that repealites are now transmitting simultaneously, which leads to the near-far effect. Thus works have also been carried out concerning this effect.

5.1 Introduction to the idea

It is rather simple in principle: synchronisation is advantageously carried out when the same single signal is transmitted by all the repealites and simultaneous transmissions allow us to implement carrier phase measurements (Vervisch-Picois et al. 2010). Multipath is always a problem but the SMICL, developed in the context of the repeater system, appears to be quite an efficient answer. The pseudolite double differencing approach is probably a little bit too complex for mass market devices (this could be discussed) thus the goal is simply to smooth the code phase measurements with carrier phase measurements, following the classical way of many current GNSS receivers.

The only remaining difficulty is now the near-far effect: a solution to this problem is proposed. Note that when both multipath effects and near-far effects have found a solution, one could consider that the pseudolite system is well suited, since two major problems are solved. As a matter of fact, this is quite true except for synchronisation purposes. Thus, the repealite approach seems to be rather an acceptable compromise.

5.2 The proposed system architecture

The proposed method comes from the transmitting approach of the repeated system, but instead of the sequential mode, the transmission on each antenna is delayed in such a way that the transmitted signals on each repealite do not interfere once they arrive at the receiver

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[26] Repealite is a contraction of Repeater and Pseudolite.

antenna. A new problem arises: since a high level of interference can occur because of simultaneous broadcasting of different signals. This can induce severe interference that can disrupt the signal. If one observes the ACF at the receiver end (see figure 22), there is no longer one maximal peak for each code length, but N peaks if N is the number of transmitting repealites (assuming that all the transmissions are included in one code length, but note that this is necessary for the system).
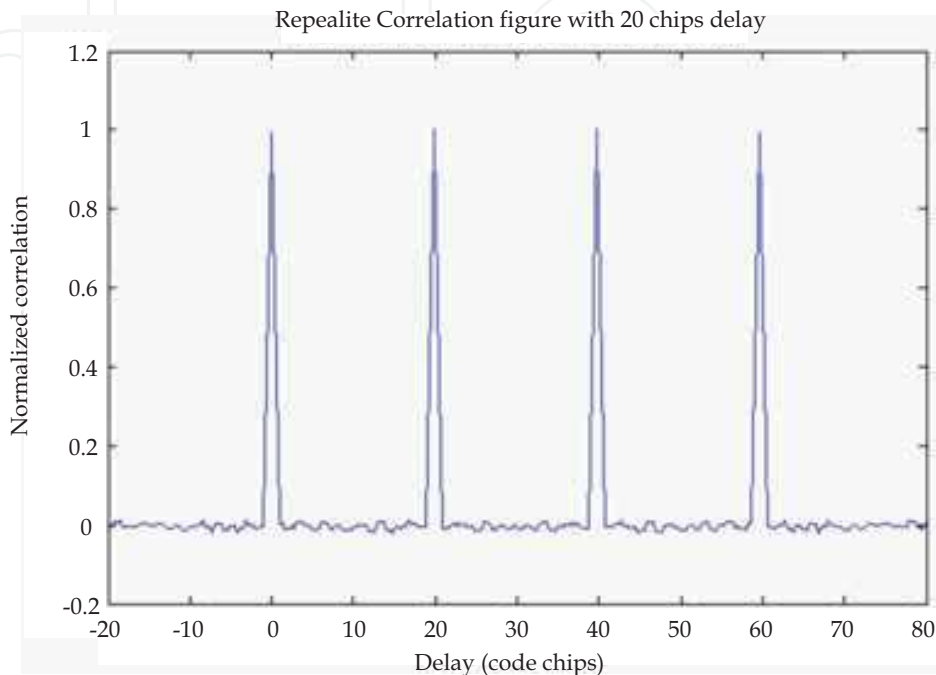

Fig. 22. The resulting auto-correlation function at the receiver

The system shown in figure 23 uses a signal generator that ensures the synchronisation. A single signal is sufficient, as in the case of repeaters.
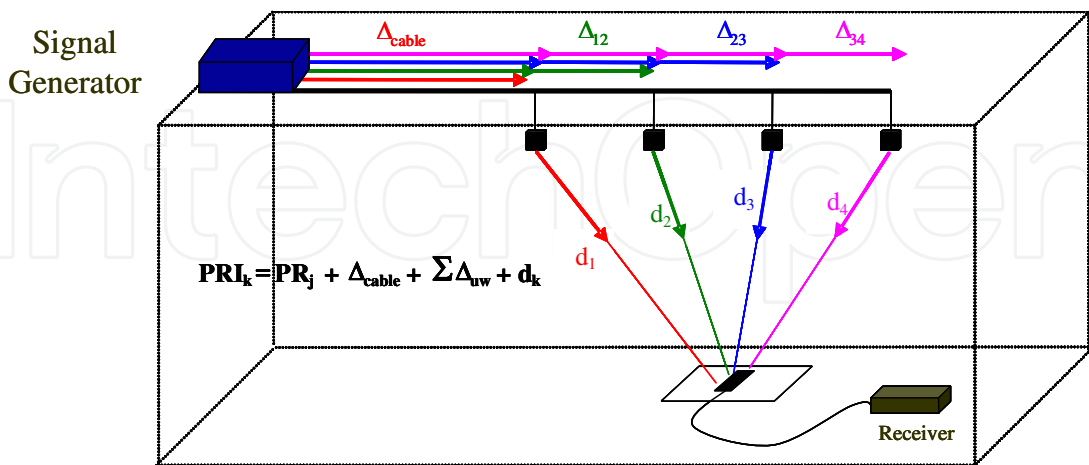
Fig. 23. The repealite system

With 4 delayed channels the terminal is able to carry out 4 indoor pseudo-range measurements. These measurements lead to the equations of the system (the notations of figure 23 are used):

$$\begin{cases} PR_1 = d_1 + \Delta_{cable} \\ PR_2 = d_2 + \Delta_{cable} + \Delta_{12} \\ PR_3 = d_3 + \Delta_{cable} + \Delta_{12} + \Delta_{23} \\ PR_4 = d_4 + \Delta_{cable} + \Delta_{12} + \Delta_{23} + \Delta_{34} \end{cases} \tag{6}$$

Where the PR_k are the indoor pseudo-ranges measured by the receiver, Δ_{cable} is the common part of the delay in the cable between the generator and the first repealite (including error and clock bias between the generator clock and the clock of the receiver), the Δ_{uw} are the delays between repealite R_u and R_w and the d_k are the indoor geometric distances between repealite R_k and the indoor receiver.

The locations of the transmitters have to be known[27], as usual, and the indoor position is computed in a local referential with a classical GNSS algorithms. Note that the velocity can also be calculated in the local referential, just like GNSS outdoors, since the contribution of the clock drift of the generator to the Doppler is common to the 4 repealites and that the only contribution of the signal to Doppler is the relative velocity between the antenna of the indoor receiver and the antenna of repealite R_i.

5.3 The main advantages

The fact that repealites are transmitting in a continuous way allows us to follow the carrier phase of the signal, a source of potential improvements in the positioning accuracy. This feature could lead to a similar operating mode to carrier phase pseudolites, but this is not the main objective here. Another interesting improvement compared to repeaters is the ability to carry out dynamic positioning with no restriction since instantaneous measurements and calculations are carried out. It is also noticeable that dynamic positioning is bound to be of better quality since the receiver movement will have a direct impact on the average multipath distribution, leading to a more efficient averaging of their effects.

The continuity with outdoor GNSS is even simplified in comparison with a repeater where a switch between the outdoor mode and the indoor mode and its cycling scheme was required. With repealites, this switch only concerns the PRN number used which should be characteristic of indoors: the same apply to pseudolites.

The last main advantage is associated to synchronisation. The fact of using a single signal is an advantage in comparison to pseudolites, but does not allow the synchronisation problem to be completely removed since transmitters still have to be synchronised. This is currently achieved through wire connections, either by coaxial cables or by the way of optical fibres[28]. The synchronisation of the system is obtained once several measurements are carried out at known locations.

5.4 The remaining limitations and the ways they are dealt with

The two most important remaining limitations are respectively the multipath and the near-far effect. Multipath effects are dealt with through the use of the SMICL. Note that good

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[27] Some works are under consideration in order to propose methods for auto-positioning the transmitters.

[28] Optical fibres are also considered for the physical realization of the time delays between repealites.

pseudo-range measurements are a must if one wants the smoothing of the code by the carrier to be efficient: thanks to the SMICL, this is possible.

We have seen that the ACF of the various codes used in GNSS present secondary peaks that are the origin of the near-far problem. In the case of the repealite based system, this problem is enhanced since the same signal is repeated N times (in the case of N repealites transmitting simultaneously). Thus, the interferences are of uppermost importance, in particular when defining the delays between repealites (since superposing the repealite signal to a secondary peak of the preceding repealite would be a particularly bad idea). Thus, a proper choice of the delays has to be carried out in coordination with the code used and the size of the indoor environment (because the signals should not interfere at the receiver).

A few approaches have been proposed in order to reduce the near-far effect in the case of repealite systems, depending on the codes used. For the GPS codes, it appears that the appropriate delays are obtained when the ACF is close to zero (see figure 24): such "locations" are numerous but depend on the chosen code (the locations are not identical for all codes). In order to reduce the near-far, a double transmission technique is proposed: it consists indeed in modifying the shape of the transmitted signal in order to allow the receiver to carry out differences that could allow it to remove the most powerful signal which is the cause of the near-far. The signal sent is composed of the initial code to which is added, in opposite phase, the same signal delayed by half a chip. Improvements of up to 30dB in comparison with solutions where no near-far mitigation techniques are implemented have been reported. Note that this means still 20dB of improvement in the power that can be managed in comparison with a pulsed pseudolite system.
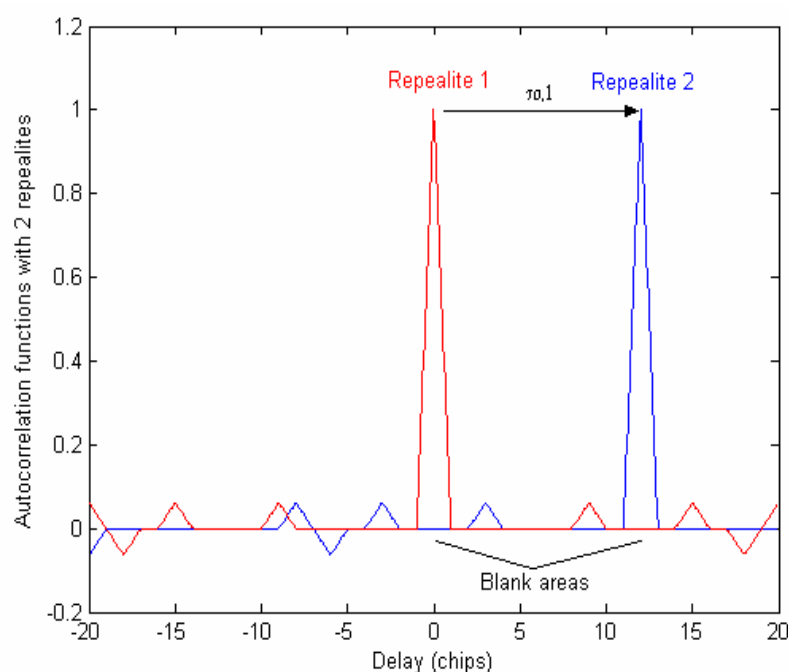
Fig. 24. Optimal determination of the delays between repealites

The drawback of this approach is that it requires a specific signal to be sent and in turn a modification of the software of the receivers which have to be aware of this specific mode. Nevertheless, the efficiency theoretically demonstrated may be worth implementation.

Another interesting proposition concerns the potential use of maximal sequences that have the advantage of providing us with a unique value of auto-correlation outside the main peak (Vervisch-Picois and Samama 2009). Thus, it is possible to carry out differences without the need for a half chip delay for the additional signal. The implementation is then quite easy and can be applied to an almost unlimited number of repealites.

In these cases, interference with outdoors is a very interesting and challenging topic since regulations are appearing in order to "preserve" the GNSS bands. The fact of using similar codes to those used outdoors is a real concern which could find an elegant solution through the use of originally designed sequences. Of course, a frequency shifted approach would definitively solve the interference problem with outdoors, but would require new frequency resources in the case of the modern Code Division Multiple Access (CDMA) GNSS systems.

5.5 A few preliminary estimated performances

The smoothing of the code with the carrier phase is a very classical operation in GNSS. It consists of using the low noise carrier phase measurements in order to smooth the pseudo-range measurements. It is very efficient in order to reduce thermal noise but not really for multipath. Thus, the coupling of the SMICL with this smoothing technique is a very nice combination. The Kalman filter implemented is then nearly optimal. Note that indoors, the main error source comes from multipath, since no atmospheric contributions or clock bias errors of transmitters (in this repealite based configuration) are present. In the present case, the filter uses the carrier phase measurement in order to carry out its estimation of the future state.

Simulations have been carried out considering a circular displacement of a pedestrian in a place where a severe multipath (only one) is present, sometimes of even greater amplitude than the direct path from a transmitter. This is achieved through a perfect reflector located in the close vicinity of the trajectory. As can be seen in figure 25, the repealites are located in
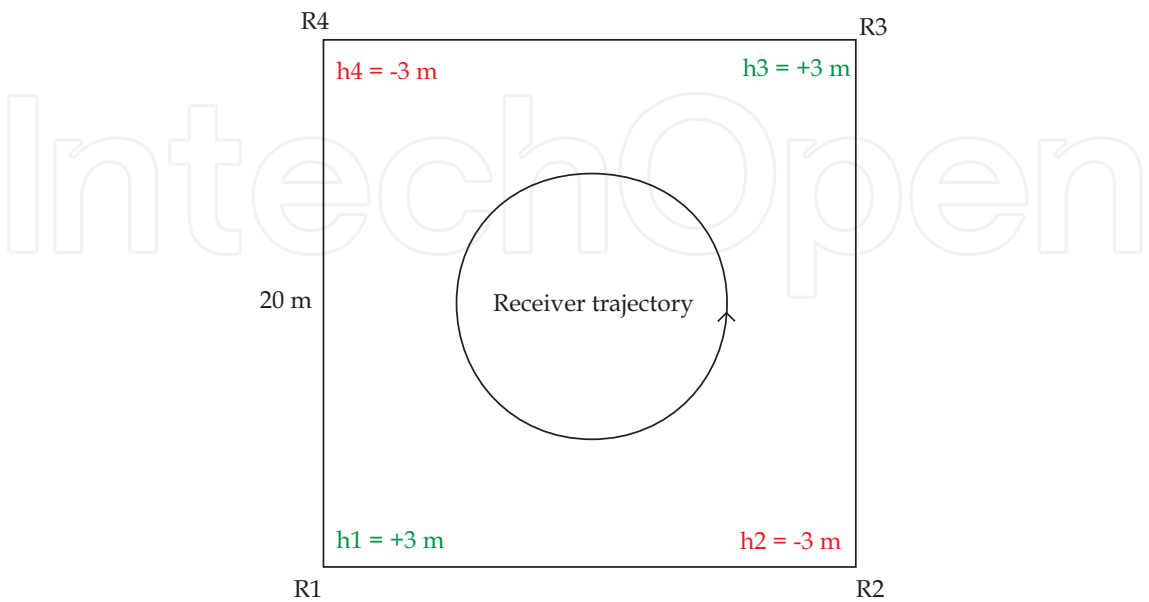
Fig. 25. Considered trajectory and repealite distribution

the corners of a square that includes the complete trajectory. Their exact locations are given in the figure (note that the altitude of the repealites are also given and allow for quite a nice indoor VDOP). The receiver is considered to be at an altitude of zero meters.

The speed of the receiver is set at 1m/ s and the multipath delay appeared to vary between 0.07 and 0.17 chips, equivalent to between 20 and 50 metres roughly. Note that since the SMICL is more sensitive to noise than the SDLL (or the NC), the simulations were carried out using 50dB-Hz for the C/ N0 value. This is rather a high value for outdoors, but not impossible indoors since one decides the indoor power transmitted (except that regulations are limiting the maximum allowed).

The results are given in figure 26 for 2D and 3D positioning. These simulations show a few decimeters accuracy range for the whole trajectory, and results a little bit better for 2D than 3D. Some skips can be seen in figure 26 which are the ambiguity skips: thus, these skips are typically a multiple of nineteen centimeters. This allows us to evaluate the efficiency of the estimation of this ambiguity. Note that it is calculated every second and is based on the SMICL assisted measurement of the code phase. This once again confirms the very good performance of the SMICL approach.
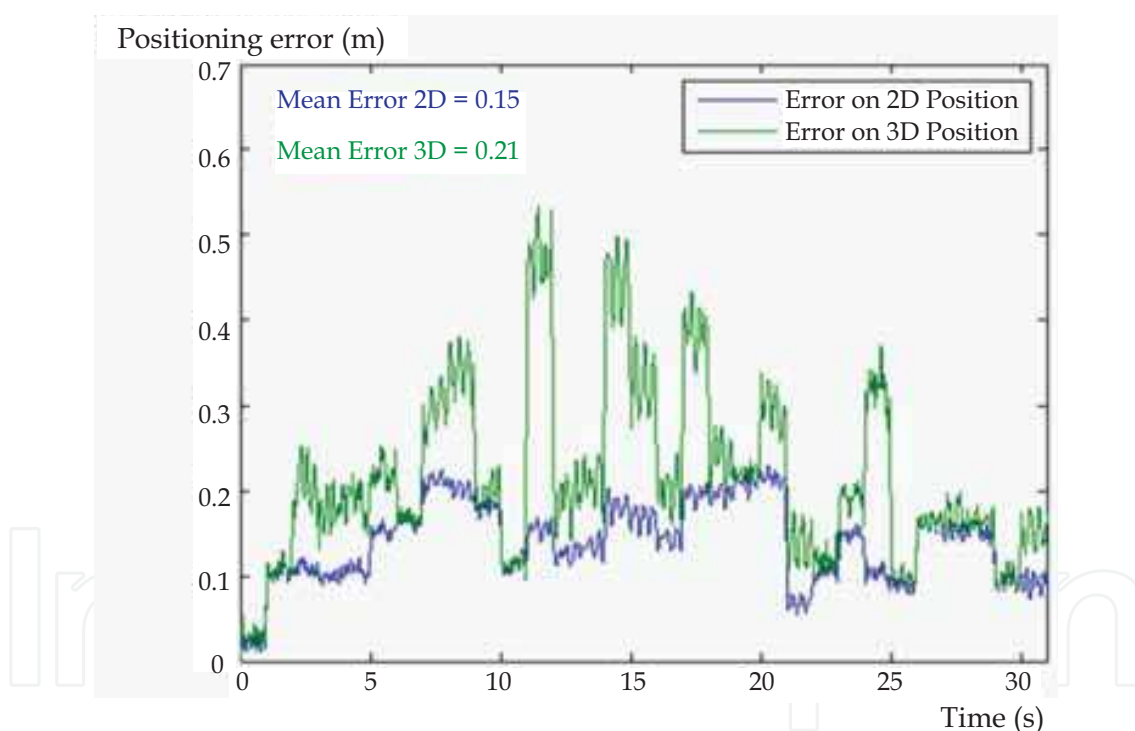
Fig. 26. Positioning accuracy obtained with a repealite system

6. Regulatory issues for L1/E1

The problem of using the same frequency band as the outdoor GNSS is that interference may occur. Of course, when a single system is deployed, these interferences should be very limited and only disturb locally the outdoor receivers. Nevertheless, if no regulations exist, there is a potential danger for GNSS. Thus, some countries have worked towards the development of constraints on the power allowed to be transmitted.

6.1 General introduction

The problem is due to the inter correlation functions (ICF) of the various code sequences that are used. As a matter of fact, these ICF have small peaks, comparable to the secondary peaks of the ACF. If the number of the ground based transmitters is too high or if the total power is too high, then the addition of these secondary peaks is likely to generate interferences to an unacceptable level for outdoor receivers.

Two different cases have been considered by the regulatory authorities: the repeaters and the pseudolites. The repeater case corresponds to a transmitter which uses the outdoor available signals and, after amplification, retransmits them indoors. The ICF between indoor signals and outdoor ones can been considered as being indeed ACF, thus leading to potentially higher interferences. Thus, the maximal acceptable power associated with repeaters is lower than for pseudolites[29].

6.2 The case of the repeaters

In the United States it is not legal to sell GPS repeaters and only the Federal government or agencies operating under its direction, parties that would have received either a Special Temporary Authority (STA) or an Experimental License, or parties operating in an anechoic chamber are authorised to use such devices.

In Europe, things are a little bit different and regulations are based on the Electronic Communications Committee (ECC) report 145 (ECC report 145), dated May 2010. Studies were carried out on the base on interference evaluations in the various GNSS associated frequency bands. Let us concentrate on the L1 band (1559 to 1610 MHz). The global conclusions are as follows:

- The maximum gain of the repeater, from outdoor antenna to indoor antenna should be limited to 45dB.
- The radiated power[30] should not exceed -77dBm.
- The maximum power re-radiated that are not GNSS signals should be less that -20dBm.
- The repeater should include filtering.

Some experimental results presented in previous sections were carried out with -80dBm and have shown acceptable performance within a typical range of 20 metres.

In addition to the above technical recommendations, report 145 states that any authorisations should include guidance instructions in order to help the applicant in the deployment phase of the repeaters. Also, particular attention is recommended for installations close to airports or to military sites.

Finally, the report proposes that any uses of repeaters should be subject to individual authorisation and that no mobile use should be permitted.

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[29] Please note that the various indoor positioning systems proposed in this chapter have to be considered as « pseudolite based » for regulation purposes, although the so-called « repeater based » approach could also be implemented using repeaters (in the sense of the regulations), and then fall into the corresponding regulation, of course.

[30] The so-called eirp (Equivalent isotropically radiated power).

6.3 The case of indoor pseudolites

The GPS predicted the need for terrestrial generators when reserving the specific codes, PRN 33 through 37, for ground transmitters. Galileo also included the possibility of using such transmitters. Note that since codes are different from satellite's ones, the limitations are a little bit relaxed in comparison to repeaters.

The following lines are based on report 168 of the ECC (ECC report 168), dated May 2011, and relate to indoor pseudolites. Similar to the case of repeaters, computations were carried out on the base on interference evaluations in the various GNSS associated frequency bands. For the L1 band, the main conclusions are as follows:

- The radiated power should not exceed -50dBm.
- The antenna of the pseudolite should point at the ground and be directed towards the inside of the building.
- The radiated power for an elevation angle superior to 0 degree should be reduced by more than 6dB.
- The radiated power should be reduced to -59dBm in airport areas and specific mitigation techniques implemented when aircraft are in their parking stands.

Note that the power level is rather high in comparison to repeaters and largely sufficient in order to have all the techniques described in the chapter implemented in real conditions with good performance. As a matter of fact, the estimated range with -60dBm is around one hundred metres in real environments, i.e. including walls and multiple floor levels (ceilings). The remaining 10dB margin could be used in order to provide the receiver with a high SNR, required for the SMICL for instance. On the other hand, the interesting feature that consists in positioning a pseudolite on the ground pointing at the top of the building (in order to substantially increase the VDOP) will have to be implemented with a 6dB reduced maximal power.

In addition, report 168 states the same as for repeaters concerning individual authorisations, insertion of guidance instructions in order to help the applicant in the deployment and interdiction of mobile pseudolites. It is also proposed that some authorities (military, government and meteorological services) be allowed to apply for specific site limitations.

Moreover, the report mentioned that longer codes could improve both the compatibility with non-participative receivers and the performance of participative ones. Note that research works are on-going in this direction.

7. Synthesis and future trends

The GNSS-like signal indoor positioning systems, either based on pseudolites, repeaters or repealites are a real alternative in order to provide users with a continuous service, at the cost of deploying a local infrastructure. This is now possible in particular thanks to multipath and near-far effect mitigation techniques. Performance attainable is in the metre range through rather good quality measurements and elementary computation algorithms. In comparison, such solutions as WiFi based ones, are based on low quality measurements (power level typically) and complex computation algorithms.

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Global Navigation Satellite Systems: Signal, Theory and Applications

Edited by Prof. Shuanggen Jin

Global Navigation Satellite System (GNSS) plays a key role in high precision navigation, positioning, timing, and scientific questions related to precise positioning. This is a highly precise, continuous, all-weather, and real-time technique. The book is devoted to presenting recent results and developments in GNSS theory, system, signal, receiver, method, and errors sources, such as multipath effects and atmospheric delays. Furthermore, varied GNSS applications are demonstrated and evaluated in hybrid positioning, multi-sensor integration, height system, Network Real Time Kinematic (NRTK), wheeled robots, and status and engineering surveying. This book provides a good reference for GNSS designers, engineers, and scientists, as well as the user market.

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