Context-aware Peer-to-Peer and Cooperative Positioning

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Abstract— **Peer-to-peer and cooperative positioning represent one of the major evolutions for mass-market positioning, bringing together capabilities of Satellite Navigation and Communication Systems. It is well known that smartphones already provide user position leveraging both GNSS and information collected through the communication network (e.g., Assisted-GNSS). However, exploiting the exchange of information among close users can attain further benefits. In this paper, we deal with such an approach and show that sharing information on the environmental conditions that characterize the reception of satellite signals can be effectively exploited to improve the accuracy and availability of user positioning. This approach extends the positioning service to indoor environments and, in general, to any scenario where full visibility of the satellite constellation cannot be granted.**

I. INTRODUCTION

Positioning based on Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS) or GLONASS and Galileo, is widely used as a primary technology to obtain the estimation of the user position in mass-market personal devices as smartphones. Despite its widespread use, there are still several limitations in the use of GNSS in environments where the signal is attenuated and where a line-of-sight path between the receiver and the satellites cannot be achieved.

Assisted-GNSS (A-GNSS) service has been introduced to enhance the performance of GNSS-based positioning, broadcasting from fixed stations, through the mobile communication channels, pieces of information that aim at improving the performance mainly in terms of time required to obtain the first position and of receiver sensitivity[1][2]. Nevertheless, A-GNSS cannot overcome the limitations of a reduced visibility of the satellites, as it is often the case in light indoor environments or urban canyons. For this reason, the concept of Peer-to-Peer (P2P) and cooperative positioning has been recently introduced as a way of providing users in harsh environments with aidings obtained by locally processing pieces of information collected from other GNSS users [3][4].

The positioning procedure is then driven by the context through the cooperation with other users, so as to increase the availability of the positioning service. Context-aware positioning requires users to share information about the environment in which the GNSS receivers are expected to operate. Such “local” information, in some cases, may be more effective and, in a way, complementary to the A-GNSS messages.

Two similar architectures can be envisioned for the implementation of such context-aware positioning. P2P positioning exploits communication links between two or more neighbors (or peers), thus relying on an unstructured network without a control or a data fusion center. Instead the definition of cooperative positioning is more general: although it relies on communication among peers, the positioning of one or more users may be performed by a control center collecting information from a number of cooperative users. In both architectures, receivers exchange data that embed information about the environment, thus easing the procedure of user positioning.

Recent research projects have demonstrated the benefits of this approach in terms of reduction of the signal acquisition time when GNSS aiding quantities like Doppler, satellite carrier-to-noise ratio (C/N0), and secondary code delay estimates are provided by some aiding peers [5][6][7][8]. In terms of availability of the positioning service, the typical scenario in which peer-to-peer or cooperative positioning may be beneficial with respect to the standard A-GNSS is when a user does not have a sufficient number of satellites in view. In fact, it is well known that in order to obtain its position, a user receiver has to solve a positioning problem which includes the 3 spatial unknowns and the local clock bias. Thus, the user needs ranging measurements from at least 4 satellites in line-of-sight, which due to the clock bias, are named pseudo-ranges.

Figure 1 shows a scenario that is typical of urban and light indoor environments. A user (aiding peer) has sufficient visibility of the satellite constellation, while the aided-user, due to the presence of local obstacles, misses one satellite measurement and cannot estimate its own position. In order to let the user obtain a PVT (Position, Velocity, Time) solution, two kinds of context-aware aidings are possible:

1. The aiding peer shares its altitude information thus allowing the aided peer to solve the positioning problem for 3 unknowns only;

2. The aiding peer shares one measurement of a pseudorange from a satellite that is not visible to the aided peer. This second solution strongly depends on the distance of the aiding peer from the aided one and implies very sensitive

synchronization problems. In fact, the measurements are affected by the synchronization bias of each GNSS receiver, which may or not compensate the pseudorange measurement with such a bias contribution. This second approach significantly increases the complexity of the aided position procedure.

Even if the aiding concept seems to be quite trivial, the actual implementation inherits several issues that require the users to share more information than just the altitude of the aiding peer. Indeed, the full set of coordinates (and time epoch) of the aiding peer is necessary, not only to reduce the number of unknowns in the equations, but also to aid the starting of the PVT iterative calculation. The initial PVT estimate affects the convergence time of the positioning procedure and it is used to assess the position of the visible satellites, whose orbital parameters are contained in the navigation message of the GNSS signal. Furthermore, there are a number of propagation corrections that are location-dependent (ionospheric and tropospheric corrections), which must be applied to the measurements during the PVT solution. In absence of a good initial PVT estimate, the above-mentioned corrections can be applied only after a number of iterations assuring that the positioning algorithm is close to convergence.

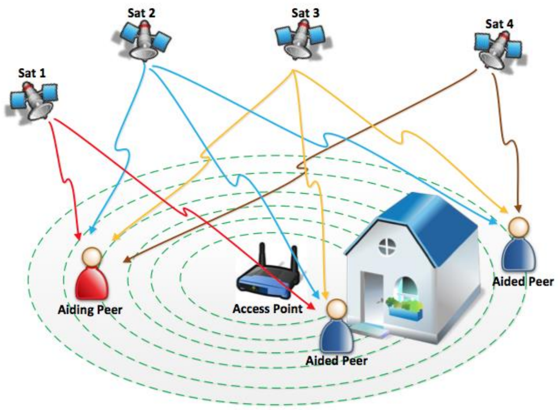

Figure 1. Typical urban and light indoor scenarios

In order to implement such P2P architecture, both the networking and application aspects as well as the aided-positioning algorithm have to be addressed.

Working at application layer, the P2P architecture can be implemented already in nowadays mass-market terminals. As for the positioning procedure, the current limitation is that typically the information about pseudoranges is not computed by the GNSS chipsets embedded in the user terminals. However, depending on the chipset in the smartphones, such information can be retrieved with a proper application and the PVT algorithm exploiting the altitude information can be implemented outside the chipset itself, as an independent application.

In the following we will discuss the different implementation issues and provide the results of an experimental test campaign that demonstrates the benefits of context-aware positioning, in terms of service availability and accuracy.

II. Application Level

The physical networking technologies that we adopt for the exchange of information among peers are WiFi and Bluetooth. Both are currently available on regular mass-market devices (such as smartphones, tablets and laptops). The WiFi technology allows for higher throughput (up to 600 Mb/s using the IEEE 802.11n), wider coverage and faster session setup compared to Bluetooth. However, while Bluetooth permits to create direct point-to-point connections between devices, WiFi typically requires the presence of an Access Point (AP).

The application layer we implement is based on an open source, peer-to-peer software called AllJoyn [9]. This tool enables ad-hoc, proximity based, device-to-device communication. It aims to support as many different operating systems and networks as possible, in order to create P2P networks with different types of devices, such as smartphones, tablets and laptops. Mobile devices running this platform can dynamically discover other AllJoyn devices around, automatically create connections and communicate with other peers independently of the network physical layer. Other important benefits provided by this software are the possibility to dynamic establish and handle the connection in a transparent way for the users, a service advertisement protocol and a security mechanism.

As mentioned, AllJoyn can be implemented on top of either Bluetooth or WiFi technologies. Regarding Bluetooth, the AllJoyn platform handles the creation and the management of a piconet. As for WiFi, the communication between devices takes place only if an AP is available as intermediary node (currently, solutions for direct device-to-device communication, such as WiFi Direct, are not fully supported by AllJoyn). Once devices are connected, daemons form a single bus with shared namespace. Peers are then able to discover when other peers join or leave the bus, as well as send and receive messages to a single user or to all other users. AllJoyn also provides service advertisement and discovery functions, however the discovery phase is transport dependent. Specifically, on WiFi it uses a lightweight IP multicast protocol, while on Bluetooth it exploits Bluetooth-native messages such as Extended Inquiry Response (EIR) and Service Discovery Protocol (SDP) query.

The application we develop foresees that, once every second, the aiding peer computes the satellite positions and the differential corrections using its measurement and location. It stores such data, along with the Time of Week (ToW), in a sliding window structure, that we name Observation Window. The ToW is a GNSS parameter that represents the timestamp associated with the measured pseudoranges.

Such data structure is therefore updated every second by inserting a new record and removing the oldest one. In order to provide the users with positioning information, two approaches are possible: Push and Pull. According to the Push mode, the aiding peer periodically broadcasts on the AllJoyn bus the last positioning information computed, as illustrated in Figure 2. Aided peers operating on the same bus receive such messages and process the information if interested in the service. Specifically, users compute the PVT solution by setting the altitude of the aided peer to their own. This approach is particularly beneficial when most of the users in the network are interested in the positioning service, as the communication overhead is little, and they have enough computational capabilities to derive the PVT solution.

The Pull mode is depicted in Figure 3. In this case, the aiding peer periodically advertises the positioning service by broadcasting a service announcement message on the AllJoyn bus. Users that are interested in the service send a request to the aiding peer, which then replies with the desired information. Note that Figure 2 and Figure 3 refer to the case where wireless connectivity is provided by WiFi, however a similar scheme holds when Bluetooth is used. The user request to the aiding peer includes the sender ID, pseudoranges and ToW. When the aiding peer receives a service request, it controls if it is recent enough to be served, i.e., it matches the ToW of some of the records it is storing. If fresh enough, the aiding peer associates the received pseudoranges with the computed satellites positions, it applies differential corrections, and runs the routines to compute the PVT solution, assuming that the altitude of the requesting user is the same as its own. The PVT solution is then sent in its reply to the requesting user. It is worth mentioning that the Pull approach is particularly beneficial when the network users interested in the positioning service have scarce computational resources, or their number, hence the communication overhead, is limited.

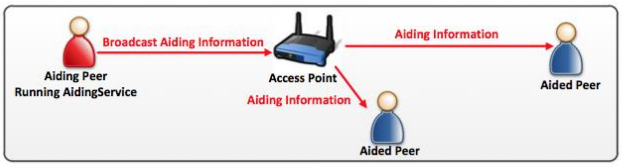

Figure 2. Push mode: The aiding peer broadcasts positioning information

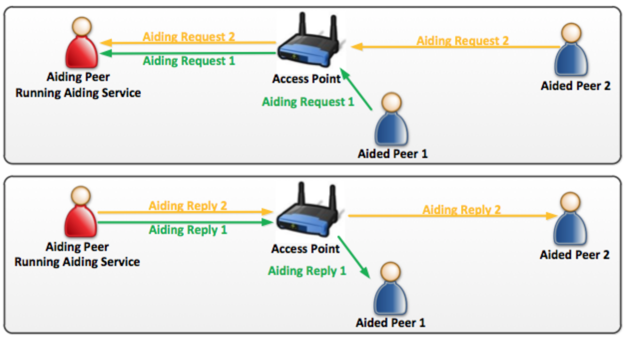

Figure 3. Pull mode: Users request positioning data, which are then provided by the aiding peer

III. The Positioning Algorithm

The first issue to address in order to implement the P2P assisted solution regards the choice of the reference frame. In fact, the position of the mobile device is provided to the users in terms of longitude, latitude and altitude (LLA) while the GPS solution is obtained with respect to the WGS84 Cartesian system, which is an Earth-Centered Earth-Fixed (ECEF) reference frame (xyz) assuming the Earth as an ellipsoid. In some cases the GPS receiver provides such a solution in a local reference frame such as the East-North-Up (ENU), which is basically a reference frame with respect to a plane tangent to the ellipsoid.

The aiding user position has then to be translated into the ECEF reference, and in particular the conversion from the ENU system may introduce additional errors since it requires to assume the coordinates of the point where the plane is tangent to the ellipsoid (i.e., what the receiver assumes to be the true user position).

In any GNSS system, a generic user needs to have at least 4 satellites in line-of-sight in order to compute its PVT solution. More precisely, for each satellite S_i placed in (x_i, y_i, z_i) the user receiver estimates a specific pseudorange $\rho_i = R_i + c \cdot \delta t_u$, where R_i is the real distance between the user and the satellite, and δt_u is the clock-synchronization bias of the user with respect to the GPS time-scale. With these measurements, it is possible to calculate the clock bias δt_u and the user coordinates (x_u, y_u, z_u) , which are the unknowns of the following non-linear set of equations:

$$\begin{cases} \rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} - c \cdot \delta t_u \\ \rho_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} - c \cdot \delta t_u \\ \rho_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} - c \cdot \delta t_u \\ \rho_4 = \sqrt{(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2} - c \cdot \delta t_u \end{cases} \quad (1)$$

However, in order to reduce the complexity, and due to the large radius of the pseudo-spheres with respect to the distances involved in the calculation of the user position, the problem is usually solved by means of a linearized set of equations. In fact, a generic pseudorange can be approximated through the Taylor expansion around a *known* approximation point $(\hat{x}_u, \hat{y}_u, \hat{z}_u)$.

Thus, being $\hat{\rho}_j$ the *known* pseudorange for the approximation point:

$$\hat{\rho}_j = \sqrt{(x_j - \hat{x}_u)^2 + (y_j - \hat{y}_u)^2 + (z_j - \hat{z}_u)^2} - c \cdot \delta t_u \quad (2)$$

the linear set of equations can be expressed in a matrix form, writing $\Delta\rho = \hat{\rho}_j - \rho_j$ as [10]:

$$\Delta\rho = H \cdot \Delta x = \begin{pmatrix} a_{x1} & a_{y1} & a_{z1} & 1 \\ a_{x2} & a_{y2} & a_{z2} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ a_{xm} & a_{ym} & a_{zm} & 1 \end{pmatrix} \cdot \begin{bmatrix} \Delta x_u \\ \Delta y_u \\ \Delta z_u \\ -c\Delta t_u \end{bmatrix} \quad (3)$$

H is a matrix containing a number of rows equal to the number of satellites involved in the position computation. Each row contains the three dimensional components (a_{xj}, a_{yj}, a_{zj}) of a unitary vector steering from the approximation point to the j^{th} satellite. Δx is the vector containing distance information between the true user point and the linearization point in ECEF reference frame and the difference between the clock bias affecting the measurement ρ_j and $\hat{\rho}_j$. Details about the linearization process can be found in [10].

In order to obtain a solution for Δx as precise as possible, an iterative algorithm has to be adopted, e.g., an iterative Least Mean Square solution, or a Kalman-filter based approach. In both cases, the iterative procedure has to be performed until the values of Δx are considered acceptable and within the uncertainty region of the position, determined by the uncompensated errors in the measurements. Recalling that in our scenario the user located in the harsh environment sees only three satellites, only three pseudoranges can be measured. For these reasons, one of the unknowns has to be fixed using the value obtained by the conversion in the ECEF format of the altitude of the aiding peer, that can be considered equal to the altitude of the aided one in most of the cases.

As we will show, the effectiveness of the aided algorithm depends on the accuracy of the altitude information as well as on the delays induced by the communication channel. Furthermore, the choice of the approximation point for the linearized solution affects the performance in terms of convergence time to an acceptable solution.

IV. RESULTS

In order to test the availability and the accuracy of the positioning service, the aided peer is emulated by a receiver connected to a georeferenced antenna, the coordinates of which are known. This allows us to evaluate the positioning error in terms of the residual Euclidean distance between the real position of the user and its final estimated location. A terminal-based aided algorithm has been implemented, and the aiding from the neighboring peers are obtained in push mode over a public Wi-Fi network.

A. *Use of the aiding peer coordinates and impact of the satellite geometry*

In order to have a comparative evaluation of the impact of the complementary coordinate value provided by the aiding peer, we tested our algorithm for position estimation by using two methods:

- The aided peer is capable of tracking multiple satellites, but only 3 randomly chosen satellites are considered. We use the aiding position to estimate the position of the aided user.

- The aided peer is capable of tracking multiple satellites, but the 3 satellites with the best geometrical distribution in the sky are chosen. It is well known that the accuracy of the position, hence the effectiveness of the aided solution, depends on the geometry of the constellation.

Figure 4 shows an example of the results obtained for the aided solution. Four placemarks are depicted:

1. Aiding peer placemark

2. Aided peer placemark: true position of the peer that is requesting the aiding and is capable of tracking 3 satellites only.

3. Estimated position placemark: output of the aided positioning algorithm when the first method is used.

4. Estimated position (Best GDOP) placemark: output of the aided positioning algorithm when the second method is used.

Figure 4. Example of aided positioning

For the case in which the z-coordinate is used by the aiding peer, considering different positions of the aiding peer (but in any case at the same altitude) ranging between 20 to 50 meters from the aided peer, the estimated position is affected by an error between 25 to 40 meters if 3 random satellites are considered to be visible. In this case the error would be of the same order of magnitude as the position of the aiding peer, i.e., the performance would be very poor. Assuming for the aided peer the same position as that of the aiding peer would be an easier way to obtain a solution with the same degree of accuracy. However, when the best satellite geometrical distribution in the sky is selected, the aided positioning algorithm provides an error ranging between 13 to 17 meters, thus allowing for a good estimation of the aided peer position.

B. *Use of the aiding peer location for initialization*

We now apply the positioning algorithm considering two different cases:

- Cold start: no information about approximation point is available, so the receiver chooses as starting point the center of the Earth (0,0,0). This is expected to be the slowest approach in terms of number of iterations required to get the solution. Furthermore the aided peer cannot effectively apply the propagation corrections until the algorithm is close to convergence.
- Assisted start: the receiver uses as approximation point the coordinates provided by the aiding peer. Since the computational time depends on how close the linearization point to the true position is, this approach is faster and more accurate since, at once, the aided peer is able to apply the corrections for the propagation delays.

The reported results reflect the average behavior of a larger number of field-test trials. In fact, in order to create a more realistic approach, we have implemented a random choice of the three satellites among the full set of the ones seen by the receiver, emulating the behavior of the aided peer. More precisely, we have used a Monte-Carlo assessment of the positioning performance averaging the results over 100 trials, for each of the spatial coordinates provided by the aiding device. Four different situations have been analyzed:

- Cold start without updating the pseudoranges corrections;
- Cold start updating the pseudoranges corrections;
- Assisted start without updating the pseudoranges corrections;
- Assisted start updating the pseudoranges corrections.

In the Assisted start the aiding peer is at about 100 meters from the aided one (see Figure 4).

TABLE I. POSITIONING ERROR FIXING THE Z COORDINATE

Scenarios	Mean position error (m)
Cold start without corrections	60.27
Cold start with corrections	43.76
Assisted start without corrections	45.45
Assisted start with corrections	40.16

As we can see from TABLE I. , using the information about the *z* coordinate and taking advantage of the knowledge of the position of the aiding peer for the evaluation of the pseudorange corrections at each iteration leads to a good improvement in the accuracy of the PVT solution with respect to the Cold Start approach. This was expected, since the validity of the ionospheric and tropospheric corrections depends on how far the linearization point is from the aided-user true position. For the same reason, an improvement can be noticed also comparing the Cold to the Assisted Start, both without corrections. Finally, we can state that the "Assisted Start with corrections" is the best algorithm in terms of accuracy at the price of a higher computational complexity, since it requires the recalculation of the corrections at every iteration step.

C. *Impact of the network latency*

In the previous examples the context-aware aiding was based on the exchange of one dimension of the time-position solution of the aiding peer. Such information is used within the algorithm to reduce the number of unknowns. The use is straightforward when a Least Mean Square solution is implemented. One alternative strategy may be to directly use the value of a pseudorange from a satellite that is not visible to the aided peer. The use of the aiding pseudorange is mandatory in case a Kalman-based iterative PVT solution is used.

However, recall that, in GNSS-based positioning, the positioning procedure requires a consistent set of measurements, which have to obtained at the same epoch time. In fact, the satellite constellation is constantly evolving, and consequently the value of the pseudoranges changes of several meters per second. Furthermore, it has to be assumed that the aiding peer receiver has already compensated the measurements for the bias of the local clock.

The aided positioning algorithm has to take into account the consistency of the measurements. In fact, even for static, or slowly-moving users, large delays between the set of measurements of the aided peer and the time epoch at which the aiding measurement was performed, may affect the solution accuracy. Thus, the delay introduced by the WiFi network has to be carefully considered. The session setup time and the delay with which a message is transmitted may not be negligible, especially in condition of overloaded networks. In a pull architecture also the time needed to perform the request has to be taken into-account. One way to mitigate the problem is the inclusion of the ToW in the set of aiding parameters. In this way, the aided node can evaluate the difference between its ToW and the received one, and compute the PVT solution using the correct data. However, since in some cases aged aiding data have to be used anyway in order to obtain a position that would not be otherwise possible, the impact on the accuracy has been assessed.

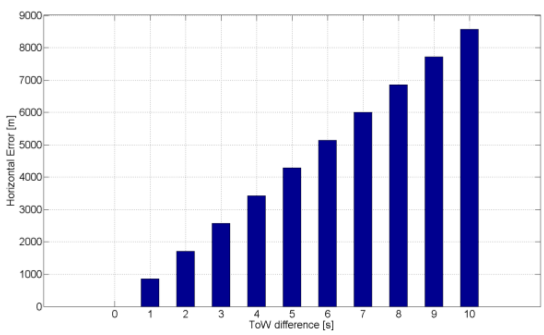

Figure 5. Degradation of performance due to network lag

Figure 5 shows the impact on the horizontal error with respect to delay between the ToW of the pseudoranges of the aided peer and of the aiding one. As it can be noted, the impact of the ToW difference is not negligible: only few seconds of delay cause an error of the order of kilometers, making the entire procedure useless. For these reasons, assuming that both peers are static, a memory buffer should be implemented in order to merge consistent measurements in the PVT solution.

CONCLUSIONS

The concept of context-aware P2P or cooperative positioning is gaining increasing attention as a mean to improve the performance of GNSS positioning in those denied GNSS environment where a standalone receiver-based positioning fails.

The paper has shown a set of on-field tests proving the benefits given by the use of a P2P architecture based on mass-market devices and demonstrated that cooperation between peers sharing information about the environment increases the availability of the positioning service. Different aiding scenarios have been analyzed, and different aiding information integration algorithms have been assessed and compared in terms of positioning accuracy and availability. Our results have shown that, beyond the quality of the aiding information provided to aided peer, the geometry of the few satellites visible to the aided peer has a not negligible impact on the position accuracy. Furthermore, the delay due to the communication network can severely degrade the accuracy of the performance if the aiding pseudoranges are used to complement the data available at the aided peer location. For these reasons, integration of aidings at the PVT level, such as integration of altitude (or any other coordinate) of the aided peer, results in a more robust solution for static and slowly moving users.

Our analysis also shows that P2P and cooperative positioning could be beneficial in several practical cases and that tailoring the system architecture and the algorithms to specific application scenarios could improve the positioning performance dramatically. In particular, the proposed approach could be a valuable solution in vehicular networks, due to the evolution foreseen for car-to-car communication and the limited visibility in urban environment, as well as in light indoor and emergency applications. As multi-standard devices will become more and more inter-connected in the near future, GNSS cooperative positioning may soon become an alternative or a complement to other kind of aiding systems.

Possible directions for future research include the definition of the format of the aiding information to be broadcast and the communication network so as to achieve the best trade-off between the amount of shared information and the aided peers' requirements.

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