Cooperative GPS Positioning with Peer-to-Peer Time Assistance

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***Abstract*—In this work, a peer-to-peer cooperative positioning technique is presented, implemented and tested. Cooperation between two Global Positioning System (GPS) software-defined receivers is realized by resorting to an ad-hoc WLAN. The performance of aided acquisition and positioning algorithms with fine and coarse time assistance is evaluated. The fine time assistance is achieved by an ideal off-line synchronization technique, while the coarse time one is carried out by means of Network Time Protocol (NTP).**

Keywords*—*GNSS receiver; Software-defined; Peer-to-peer; Cooperative; Coarse-time; Positioning;

I. INTRODUCTION

Modern mobile communication devices, such as smartphones, integrate different systems, i.e. WiFi, 3G, Bluetooth, Global Navigation Satellite System (GNSS), to provide multiple functionalities and services, aiming at being user friendly at the same time. Among smartphone owners, the number of people using location based services (LBS) is growing rapidly. From the business side, the localization allows to know and analyse users, not only from an analytic point of view, but also for what concerns their behavior, assuming always more a social value. In this context, the LBSs help the user to interact with the surrounding place and the people nearby. Moreover, the growing importance of position-based applications, such as rescue [1], [2] and commercial operations or maritime and aviation applications, pushes GNSSs such as GPS [3] to assume an important role nowadays. In order to provide global LBSs, the effectiveness of the GNSS systems is mandatory. In hostile conditions, where the Line-Of-Sight (LOS) to the satellites is partially or totally obstructed, such as in urban canyons, foliage environments and indoor locations, the received signal strength from satellites to GNSS receivers might be too weak for an appropriate processing, leading the GNSS-based localization to degrade or even fail. Peer-to-Peer Cooperative Positioning (P2P-CP) [4], [5] can be a solution, since it aims at improving the GNSS receiver performance in terms of availability, accuracy and Time-To-First-Fix (TTFF). P2P-CP exploits the direct communication between single nodes to exchange GNSS aiding information, leading to a flexible architecture and exploiting more effectively the local environment. In aided GNSS approach, the time synchronization between aided and aiding receivers is of capital importance for the exchanged information reliability: both the acquisition and the positioning procedures can be harmed by the lack of an accurate synchronization. As for the implementation issues, the inherent limits of the traditional hardware-based GPS receiver can be overcome by Software-Defined Radio (SDR) technology. SDR solutions afford a flexible architecture for the receiver, and allow a dynamic selection of parameters for individual modules. In the present work, a peer-to-peer cooperative positioning technique has been implemented and tested. The cooperation is carried out by two GPS software-defined receivers, namely the aiding and the aided receivers, both implemented in MATLAB. The aiding receiver works in stand-alone mode [6], while the aided one implements assisted acquisition and positioning algorithms with fine and coarse time assistance. Depending on the aided receiver location environment, two scenarios are considered: Outdoor-to-Indoor (O2I) and Outdoor-to-Outdoor (O2O) (Fig.1). The former refers to an aided receiver located indoor while the aiding device is outdoor; on the other hand, the latter is related to the case of two outdoor receivers. Two tests are considered for each scenario: the first one refers to an off-line ideal synchronization between the aiding and the aided receivers in the context of fine-time assistance, while the second one is relative to a context of coarse-time assistance where the receivers are synchronized by means of NTP. The acquisition and positioning performance is evaluated in case of both fine and coarse time assistances. In this paper, the authors want to extend the work presented in [7], by testing the P2P cooperative positioning technique in different environments and providing also a statistical description of the aided receiver positioning accuracy in both the O2I and O2O scenarios.


(a) (b)

Fig. 1. a) Outdoor-to-Indoor scenario. The green and red circles represent the aiding GPS receiver located outdoor and the indoor aided one, respectively. b) Outdoor-to-Outodoor scenario. Both the aiding (green circle) and the aided (yellow circle) receivers are located outdoor.

II. FINE/COARSE TIME ASSISTANCE IN P2P-CP

The synchronization between GNSS receivers in cooperative positioning schemes plays a fundamental role [8]. In LOS condition, the GNSS receiver decodes time-of-week (TOW) information from the navigation data which is transmitted by the satellites. This information is required to form the complete pseudorange measurements. In the case of weak signal reception, the GNSS terminal may not reliably decode the TOW due to high Bit Error Rate (BER) so that it has to resort to external assistance data in order to compute a reliable position fix. Aiding information can include a combination of approximated user position, ephemerides, almanac, time and frequency assistance. Concerning the time assistance, fine-time acquisition process is assumed when the synchronization error (between GNSS receivers) is <1 ms, whereas, if dealing with positioning, fine-time assistance refers to synchronization errors that are <10 ms [8]. Fine-time assistance not only relieves the receiver but also helps in accelerating signal acquisition through narrower search windows either in frequency or in time domain, so improving the TTFF. Moreover, the fine-time assistance allows to increase the receiver sensitivity by extending the signal integration time during the acquisition process. On the contrary, the coarse-time assistance cannot be used directly. This is due to the large errors in satellite position resulting from time uncertainty. Since the satellites move at high velocity, the time error that is caused by the coarse-time assistance leads to an error in computing the satellite position at the transmission time. The maximum pseudorange rate of a GPS satellite is about 800 m/s. A TOW estimated within ± 1 seconds, when used to compute satellite position leads to a maximum geometric range error of 800 meters. User position derived using such measurements can be mistaken by several kilometers [9]. When only coarse-time assistance is available, the receiver can estimate the relative error as an additional unknown in the navigation solution, i.e. in addition to the usual four unknowns, namely the user spatial coordinates and the clock bias.

The estimate of TOW by coarse-time navigation algorithms is advantageous in terms of:

- Faster TTFF;
- Definition of the position fix starting from a signal whose power level is below the data decoding threshold;
- Energy saving due to the use of very short data to get a position fix.

Even if the relative satellite velocity is the reason of coarse-time positioning errors, it can play a positive role to find the solution: particularly, the information relative to the satellite velocities and the a priori receiver position, which is provided as aiding information by the external assistance, allow to compute the relative satellite-receiver velocities. The latter can be included in the set of navigation equations to be solved for: the unknown position, the unknown receiver common bias, and the unknown coarse-time error. To understand what happens if we ignore a coarse-time error, we have to understand how the vector of a-priori measurement residuals is formed in [8]. The following information set is typically required to get an estimate of the five state solution:

- A valid set of ephemeris (to obtain satellite positions and their relative velocities);
- Approximate user position within few kilometers;
- Approximate TOW accuracy within few seconds.

In the P2P-CP situation, the a priori information required for coarse-time positioning can be given by an aiding receiver. By exploiting the aiding information, the sub-millisecond pseudorange can be computed by the aided receive. The integer-millisecond pseudorange has to be added to the sub-millisecond to obtain an unambiguous pseudorange measurement. This operation has to be handled properly to avoid position error resulting from a combination of sub-ms clock bias, measurement noise, and sub-ms pseudorange. This combination could fall close to the one millisecond boundary, thus leading to one rollover on some measurements. In [8],[10] an algorithm for solving millisecond ambiguity is described.

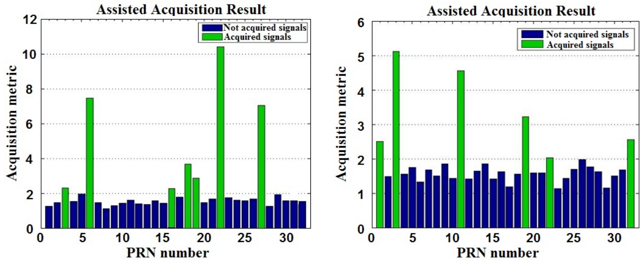
III. EXPERIMENTAL SETUP

A peer-to-peer cooperation algorithm with coarse/fine time acquisition and positioning is implemented on GPS software-defined receivers. Cooperation is carried out between two GPS software receivers (not far from each other), namely the aiding and the aided receivers. The aiding receiver is a stand-alone GPS software receiver which is implemented in MATLAB [6] : it is able to perform acquisition (through a fast parallel acquisition technique, in which the correlation function is evaluated by means of FFT operations), code and carrier tracking, navigation bit extraction, navigation data decoding, pseudorange estimations, and position computations. Also the GPS aided receiver is implemented in MATLAB and performs assisted acquisition and positioning algorithm with fine/coarse time assistance. In this experiment, both the software receivers run over common laptops and process data which is sampled at 16.368 MHz. The sampled data is achieved from a front-end module (Sige GN3S v3 [11]), which is connected via USB to the laptops. The front-end processes the satellite signals (L1 GPS signal at 1575.42 MHz) that is received from a GPS patch antenna; after filter, amplifier, mixer and ADC blocks, it provides a sampled output. The receivers are connected through an ad-hoc Wireless LAN: they exchange assistance and synchronization data. In the coarse time context, both the receivers run a background application implementing an NTP protocol which is used for coarse synchronization. The aiding receiver is a time server while the aided one is considered to be the client. The scenarios considered in this paper are illustrated in Fig.1. In particular, the Fig.1a represents the Outdoor-to-Indoor (O2I) case: it shows the aiding receiver which is located outdoor (with LOS condition to the satellites) about 20 meters away from the aided receiver, which is indoor (in no LOS condition) at the second floor of a single residential house. On the other hand, the Fig.1b illustrates the Outdoor-to-Outdoor (O2O) scenario, where both the aiding and the aided receivers are located outdoor (both with LOS to the satellites) about 30 meters away from each other. For each scenario two tests will be considered: the former one refers to an off-line ideal synchronization between the aiding and the aided receivers in the context of fine-time assistance, while the latter considers the coarse-time assistance, i.e., the receivers are synchronized by means of NTP protocol.

IV. EXPERIMENTAL RESULT

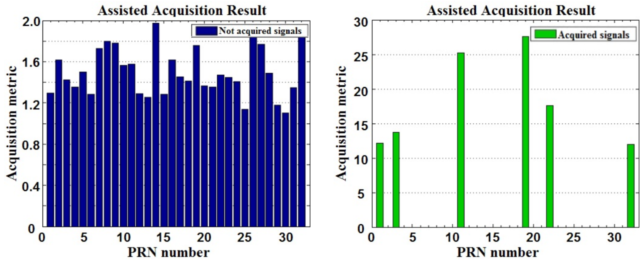
A. *Outdoor-to-Indoor (O2I) aiding scenario*

1) Fine-Time assistance: In this test, an off-line fine synchronization beetween the aiding and aided receivers has been realized.



(a) (b)

Fig. 2. a) Aiding receiver acquisition results, one ms coherent integration, one non-coherent integration, O2I scenario. b) Aiding receiver acquisition results, 1 ms coherent integration, one non-coherent integration, O2O scenario.



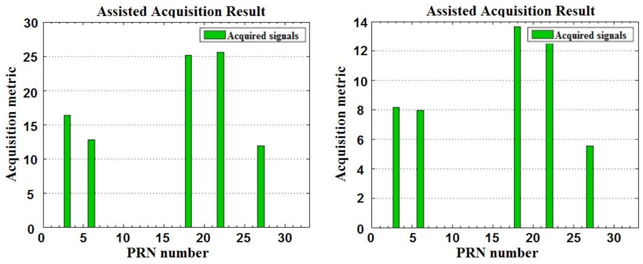
(a) (b)

Fig. 3. a) Aided receiver acquisition results, 1 ms coherent integration, one non-coherent integration, O2I scenario. b) Aided receiver acquisition results, 2 ms coherent integration, one non-coherent integration, O2O scenario.

a) Acquisition: The aiding receiver performs acquisition and tracking in the stand-alone mode: the acquisition results are shown in Fig.2a. The receiver acquires the 3,6,16,18,19,22 and 27 satellites by means of 1 ms coherent integration and 1 non-coherent integration. The green bars in Fig.2a refer to the acquired satellites. A single peak represents the ratio between the highest and second highest peak in the code delay-frequency search space for each satellite. Assuming fine-time assistance condition, the aided receiver performs an assisted acquisition thanks to the following quantities which are broadcasted by the aiding receiver:

- Satellite IDs for the visible satellites;
- Doppler frequency relative to each satellite (to reduce the frequency search space in the acquisition process);
- Time stamp of the first sub-frame of the navigation message (to identify the bit transition time).

The aided receiver will try to acquire only the satellites which are indicated by the aiding receiver. As shown in Fig.3a, it is not able to acquire satellites with a 1 ms coherent integration and one non coherent integration due to the weak received signal strength which is due to the indoor location. Therefore, its sensitivity has to be improved. In the fine-time acquisition case, the aided receiver can precisely know where the bit transitions of the navigation message occur. Thus, it can wipe off the signal from the navigation message end extend the coherent integration period to increase the receiver sensitivity. Hence, the coherent integration time can be set equal to 20 ms and 5 non-coherent integrations are used. The acquisition results with the new integration parameters are shown in



(a) (b)

Fig. 4. a) Aided receiver acquisition results, 20 ms coherent integration, 5 non-coherent integrations, fine time assistance, O2I scenario. b) Aided receiver acquisition results, 11 ms of coherent integration, 9 non-coherent integrations, coarse time assistance, O2I scenario.

Fig.4a. In order to compare the computational load between the aided and aiding receiver acquisitions, we have determined and compared the number of bins in the frequency search space. In the aided acquisition the overall frequency search space is defined by the uncertainty about the following parameters:

- reference-frequency assistance;
- time assistance;
- a priori position;
- aided receiver velocity.

We can ignore the last three uncertainties by assuming that the receivers are not moving and their distance is less than 1 km [8]. Therefore, the reliability of the Doppler frequencies which are provided by the aiding receiver just depends on the reference-frequency assistance. Considering the frequency assistance uncertainty related to the tolerance of the front-end TCXO (i.e. ±1 ppm), the frequency error magnitude will be up to 1.575 kHz for L1 band. That is, the frequency search space is within -1.575 to $+1.575$ kHz ($3.150 * 10^3$ Hz in overall). The frequency bin width in the acquisition frequency search space relative to the aided receiver can be determined as:

$$FW = \frac{\frac{1000}{CIT}}{2} = \frac{\frac{1000}{20}}{2} = 25\ Hz, \tag{1}$$

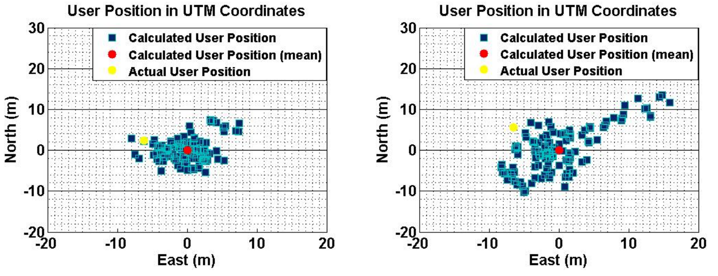
where CIT is the coherent integration time and FW is the frequency width. In conclusion, the number of frequency bins for the aided receiver acquisition is:

$$\begin{aligned} N_{\text{BIN}}(AidedReceiver)_{\text{Fine-time}} &= \frac{FSS}{FW} = \\ &= \frac{3.150 * 10^3}{25} = 126\ bins, \end{aligned} \tag{2}$$

where FSS is the frequency search space. On the other hand, the number of frequency bins for the aiding receiver acquisition is:

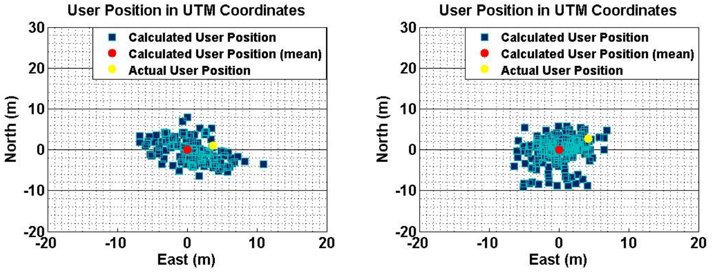
$$\begin{aligned} N_{\text{BIN}}(AidingReceiver)_{\text{Fine-time}} &= \frac{FSS}{FW} = \\ &= \frac{8.4 * 10^3 + 3.150 * 10^3}{500} = 23\ bins, \end{aligned} \tag{3}$$

where $8.4 * 10^3$ Hz is the frequency range due to the Doppler effect of satellite motion and 500 Hz is the frequency bin width resulting from 1ms coherent integration. For what concerns the computation load, taking into account the number of bins to



(a) (b)

Fig. 5. a) Aided receiver position with fine-time assistance in O2I scenario. b) Aided receiver position with coarse-time assistance in O2I scenario.



(a) (b)

Fig. 6. a) Aided receiver position with fine-time assistance in O2O scenario. b) Aided receiver position with coarse-time assistance in O2O scenario.

be scanned during the acquisition process in O2I scenario with fine-time assistance, we can conclude that the aided receiver acquisition lasts 5 times more than the aiding one.

b) Positioning: While the aiding receiver performs the positioning procedure in a stand-alone mode as usual, the aided one takes benefit from the following information that is broadcasted by the aiding terminal:

- position of the aiding receiver;
- navigation message (Ephemeris and almanac in order to compute the satellite position at the transmission time, ionospheric model and satellite clock corrections).

Once the aided receiver has accomplished the acquisition, the sub-ms pseudoranges are available. After the integer millisecond ambiguity is eliminated, the complete pseudoranges for the aided receiver are determined together with the satellite position at the transmission time thanks to the ephemeris knowledge. If fine time assistance is guaranteed, the position of the aided receiver is determined by means of Extended Kalman Filter (EKF) method (using the position of the aiding terminal as a priori position [8]).

The positioning procedure results are shown in Fig.5a, while Table I reports the mean error and the standard deviation which are relative to East and North axes.

For what concerns the computational burden of the positioning procedure, is important to note that the provision of the navigation message as aiding information causes a drastical reduction of the TTFF for the aided receiver with respect to the aiding one.

2) Coarse-Time assistance:

TABLE I. O2I STATISTICAL DESCRIPTION

	Outdoor-to-Indoor
Fine-time	$E[e_{\text{East}}]$=6.2 m , $E[e_{\text{North}}]$=2.3 m ; $\sigma_{e_{\text{East}}}$=3.7 m, $\sigma_{e_{\text{North}}}$=4.0 m
Coarse-time	$E[e_{\text{East}}]$=6.5 m , $E[e_{\text{North}}]$=5.6 m ; $\sigma_{e_{\text{East}}}$=3.4 m, $\sigma_{e_{\text{North}}}$=5.4 m

TABLE II. O2O STATISTICAL DESCRIPTION

	Outdoor-to-Outdoor
Fine-time	$E[e_{\text{East}}]$=3.7 m , $E[e_{\text{North}}]$=1.1 m ; $\sigma_{e_{\text{East}}}$=3.2 m, $\sigma_{e_{\text{North}}}$=2.9 m
Coarse-time	$E[e_{\text{East}}]$=4.2 m , $E[e_{\text{North}}]$=2.8 m ; $\sigma_{e_{\text{East}}}$=4.4 m, $\sigma_{e_{\text{North}}}$=4.7 m

a) Acquisition: During the acquisition procedure, the aiding receiver performs the same tasks as in the fine-time assistance case; the main difference concerns the aiding information: in this case the time stamp of the first sub-frame of the navigation message is not broadcasted. The coherent integration time of the aided receiver has to be extended to a shorter interval than in the fine-time assistance because of the bit transitions in the navigation message. In the signal acquisition test, the coherent integration time has been assumed equal to 11 ms while 9 non-coherent integrations are considered with the aim to compensate the possible Signal-to-Noise Ratio (SNR) reduction: particularly, since the aided receiver is indoor, the SNR must be improved to correctly acquire the satellite signals. The acquisition results are shown in Fig.4b. The number of frequency bins in the search space for the aiding receiver acquisition is equal to 23, as in the fine-time assistance test. Conversely, the number of frequency bins for the aided receiver is:

$$\begin{aligned} N_{\text{BIN}}(AidedReceiver)_{\text{Coarse-time}} &= \frac{FSS}{FW} = \\ &= \frac{3.150 * 10^3}{45} = 70\ bins, \end{aligned} \tag{4}$$

where 45 Hz is the frequency bin width which is defined by the choice of the coherent integration equal to 11 ms. When taking into account the number of bins to be scanned during the acquisition process, we can conclude that the TTFF part due to the aided receiver acquisition, is 3 times higher than in the aiding terminal.

b) Positioning: The aiding receiver performs the positioning procedure in a stand-alone mode and broadcasts the same aiding quantities to the aided receiver as in presence of fine-time assistance. The aided receiver computes the complete pseudoranges, but then, since now the time assistance is coarse, the time error has to be compensated to avoid satellite position errors. The compensation is performed by computing the pseudorange rates (for each satellite-receiver link) and including them in the geometry matrix [8]; afterwards, the five-state updates are computed using the EKF method.

The position results are shown in Fig.5b, while Table I reports the performance in terms of mean error and the standard deviation which are relative to East and North axes. The position error is larger than for the fine-time case mostly because of two reasons:

- in the coarse-time tests, the SNRs that are relative to the acquired satellites (depicted in Fig.4b) are lower than for fine-time assistance case (depicted in Fig.4a),

- in the coarse-time test, the pseudorange rates are included in the geometry matrix, leading to an Horizontal Dilution of Precision degradation [8].

For what concerns the computational load of the positioning procedure, it is important to note that, as in presence of fine-time assistance, the provision of the navigation message leads to a drastical reduction of the TTFF for the aided receiver.

B. Outdoor-to-Outdoor (O2O) aiding scenario

1) Acquisition: In the O2O scenario, which is shown in Fig.1b, the aided receiver does not take advantage of fine-time assistance during the acquisition: this is not surprising since, thanks to the LOS condition of the satellites, the aided receiver does not need a strong extension of the coherent integration time to increase its sensitivity. The aided receiver can exploit the Doppler information directly to reduce the number of bins, thus improving the computation performance of the receiver acquisition. In both the presence of fine and coarse time assistance, the aiding receiver performs acquisition and tracking in stand-alone mode, and the acquisition result is depicted in Fig.2b. The receiver acquires the 1, 3, 11,19, 22 and 32 satellites by means of 1 ms coherent integration and 1 non-coherent integration.

The aided receiver performs an assisted acquisition thanks to the received information which is the same of the O2I scenario. If a 2ms coherent-time integration and 1 non-coherent integration are considered, the number of frequency bins for the aided receiver acquisition, either in presence of fine or coarse-time assistance, is computed as follows:

$$
\begin{aligned}
N_{\text{BIN}}(AidedReceiver)_{\text{Fine/Coarse-time}} &= \frac{FSS}{FW} = \\
= \frac{3.150 * 10^3}{250} &= 12\, bins,
\end{aligned}
\tag{5}
$$

where 250 Hz is the frequency bin width resulting from the 2 ms coherent integration time. The number of bins in the aiding receiver acquisition can be considered the same as in (3) (i.e. N_{BIN}=23). In conclusion, in the O2O aiding scenario, the aided receiver acquisition time is about 2 times smaller w.r.t the aiding receiver acquisition time, leading to a reduction in the TTFF.

The acquisition results are illustrated in Fig.3b.

2) Positioning: The position results for both fine and coarse time assitance tests, are shown in Fig.6, while TableII reports the performance in terms of mean error and the standard deviation which are relative to the East and North axes. Also in the O2O scenario, the fine-time positioning is more accurate than the coarse-time one while the computational loads of the positioning procedure, either in presence of fine or coarse time assistances, are comparable with the ones of the O2I case.

V. CONCLUSION

In this paper, a peer-to-peer cooperative algorithm with coarse/fine time acquisition and positioning has been implemented on GPS software-defined receivers. The benefits which are implied by the use of the aiding information are described. Moreover, the experiment results allow to evaluate the computational and accuracy performance in both the acquisition and positioning procedures. In particular, acquisition and positioning results have been described in both the presence of fine and coarse time assistance between the receivers.

In O2I aiding scenario, the indoor aided receiver must increase its sensitivity, causing a computational load increase in the acquisition process, either in presence of fine or coarse time assistance. The positioning results confirm that the aided receiver position with fine-time is more accurate than the coarse-time.

In O2O aiding scenario, the outdoor aided receiver does not need to strongly increase its sensitivity. Therefore, it can directly exploit the aiding information to reduce the TTFF, even in the acquisition process, either in presence of fine or coarse time assistance. The fine-time positioning is more accurate than coarse-time positioning (as in O2I scenario) and the computational loads of the positioning procedures are comparable to the O2I scenario ones.

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